Life Cycle Assessment of Nature-based Design Solutions for Buildings and Building Retrofit

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Abstract

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In the context of energy efficiency and nature-based design solutions for buildings, this manuscript-based thesis presents a comprehensive Life Cycle Assessment (LCA) framework, applied to practical case studies, that architects, designers, and engineers may consider when conducting the environmental impact assessment of a building or design strategy.

Manuscript #1 presents the LCA framework, relevant software tools, and a methodology to assess the potential carbon offset achievable by integrating tree planting areas around buildings. The net annual carbon sequestration rate of 0.575 $kgCO_2eq/m^2$ of tree cover area is considered in this part. Then, two real case study buildings are thoroughly examined and compared: one involving a recently constructed all-electric research laboratory at Concordia University, and the other focusing on a natural gas-heated single-detached house. For the all-electric laboratory, a garden fully covered with representative urban trees could offset around 17% of the life cycle carbon emissions. For the natural gas-heated single-detached house, the offset was around 3% of the total life cycle carbon emission.

Manuscript #2 expands the results from Manuscript #1, specifically focusing on the case study of the research laboratory at Concordia. This part demonstrates how to estimate and report the environmental benefits linked to wood products, biogenic carbon storage, and end-of-life treatment of materials under various scenarios. The results from this part indicate that the set of design solutions adopted on this case study can potentially offset building's carbon footprint by 37.2% up to 83.9% when included in the LCA estimation, depending on the scenario considered.

After discussing the two manuscripts, an additional chapter explores the application of LCA in the context of building/energy retrofit. This part demonstrates the connection between the local energy profile and the potential carbon offsets achieved through the retrofit process. We analyzed the case study of a Canadian school building to illustrate whether the reduction in GHG emissions from operational energy use savings can counterbalance the environmental impacts associated with manufacturing the new envelope materials and mechanical equipment added during retrofit. The findings underscore the significance of building/energy retrofit in places where the grid-electricity relies on fossil fuel, such as Nova Scotia, but opens a discussion about the extent of the benefits in locations where electricity is currently sourced from renewables. In places like Quebec, if the existent case study building already relied on electricity for space heating, the embodied emissions associated with new components might outweigh the operational emissions savings resulting from the retrofit.

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And for the Felipe from the future, always remember the genuine happiness that accompanied the writing of these words.

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List of Abbreviations

ACH – Air Changes Per Hour

BCF – Building Carbon Footprint

BG – Base Growth

BIPV/T – Building Integrated Photovoltaics (Thermal Recovery)

CO2 – Carbon Dioxide

DBH – Diameter at Breast Hight (at 1.37 m)

EOL – End-of-Life

EUI – Energy Use Intensity

FBL – Future Buildings Laboratory

GHG – Greenhouse Gas

GWP – Global Warming Potential

HVAC – Heating, Ventilation, Air Conditioning

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory Analysis

LCIA – Life Cycle Impact Assessment

MW – Mineral Wool

NECB – National Energy Code of Canada for Buildings

O3 – Ozone

PM10 – Particular Matter

PV – Photovoltaic

SG – Standardized Growth Rate

SHGC – Solar Heat Gain Coefficient

TEDI – Thermal Energy Demand Intensity

WRB – Weather Resistive Barrier

XPS – Extruded Polystyrene

ZCB – Zero-Carbon Buildings

ZEB – Zero-Energy Buildings

1 Introduction

1.1 Overview

Among the multiple environmental impacts brought about by buildings, energy consumption has always been one of the major concerns. This led many countries to implement new standards for net-zero energy buildings (US-EPA, 2007; EU, 2010), and boosted the development of different certificate programs addressing energy efficiency, such as Passive House, LEED, and Energy Star.

However, the design and assessment of net-zero energy buildings commonly focus exclusively on the operational phase, ignoring the environmental impacts of embodied emissions in materials and equipment over building's life cycle (Lützkendorf et al., 2015). Therefore, a new awareness on accounting for whole building life cycle carbon emissions has refocused the construction industry on developing Net-Zero Carbon Buildings (ZCB) (Grinham et al., 2022), also referred to as Carbon Neutral Buildings.

Carbon Neutral Buildings are highly efficient buildings, operated using 100% fossil-free renewable energy and designed following best practice sustainable construction (CAGBC, 2022). The term 'best practice sustainable construction' stands for a number of strategies to reduce carbon emissions in buildings, such as promoting energy savings and the wellbeing of occupants through passive design, maximizing the use of recycled and nature-based materials, minimizing energy use in all stages of building's life, and creating new green spaces (WGBC, 2021).

Some projects have been integrating green areas and trees to the design as a way to improve user comfort (Perini et al., 2017; Pan et al., 2018; Cascone et al., 2019). When planted near buildings, trees can indirectly mitigate carbon emissions by moderating the local microclimate, reducing the required amount of energy related to space-cooling in the summer, as well as protecting buildings from strong winds, reducing air infiltration rates and heating loads in the winter (Akbari & Konopacki, 2005; Zhao et al., 2010).

However, there is only a small number of papers (Luo et al., 2015; Kuittinen et al., 2016; Liu, 2019) applying the direct carbon sequestration potential of green areas and trees among the strategies to offset part of a building's life cycle carbon emissions. During the growth process, trees absorb carbon dioxide (CO_2) from the atmosphere and store it as biogenic carbon in their biomass (trunks, branches, roots, and leaves) (Nowak & Crane, 2001). Hence, the incorporation of greeneries to the design of building and its surroundings can potentially help reducing their carbon footprint.

From an industrial perspective, trees can be transformed into wood products for construction or other long-term applications, and the carbon that they have sequestered during the growth process remains stored in these products, such as in the timber structure of a building. Moreover, wood products can offer a substitute to energy-intensive materials like concrete and steel (Chen et al., 2020; Pierobon et al., 2019). When they reach the end of their service life, they can be reused as raw material for secondary products like OSB and particle board (Höglmeier et al., 2013; Besser et al., 2021; Titunin et al., 2023), or applied as biofuel to power systems reliant on fossil fuels (Cesprini et al. 2020). Alternatively, wood waste can be disposed of in landfills, where anaerobic conditions limit carbon losses (emissions) from biodegradation, preserving the sequestered carbon for decades (Ximenes et al., 2015; Wang et al., 2013; Micales & Skog 1997; Ximenes et al., 2019).

With the growing emphasis on sustainable development, the Life Cycle Assessment (LCA) technique has gained importance in architectural and engineering practices. LCA can be used to evaluate the environmental impact of a building across its entire life cycle, guiding informed decision-making on design solutions that can enhance building's environmental performance. While progress has been made towards designing and constructing carbon neutral buildings, comprehensive case studies that cover the full range of building components and life cycle stages are relatively scarce in the literature. The incomplete scope of many LCA studies can potentially introduce biased benchmarking and restrict our understanding of the effectiveness of building decarbonization strategies.

In the context of energy efficiency and nature-based design solutions for buildings, this manuscript-based thesis presents a comprehensive LCA framework that architects and engineers may consider when conducting the environmental impact assessment of a building. The framework can be applied on either a conceptual design, in-use building, or retrofit solution.

The Manuscript #1 presents the LCA framework, relevant software tools, and a methodology to assess the potential carbon offset achievable by integrating tree planting areas around buildings. Within this section, two case studies are thoroughly examined and compared: one involving a recently constructed all-electric research laboratory at Concordia University, and the other focusing on a natural gas-heated single-detached house.

Then, Manuscript #2 builds upon the findings of Manuscript #1, specifically focusing on the case study of the research laboratory at Concordia. In this part, the latest LCA standards are investigated to demonstrate how to estimate and report the environmental benefits linked to wood products, biogenic carbon storage, and end-of-life treatment of materials under various scenarios.

An additional approach is presented after the two manuscripts. This approach focuses on the application of LCA in the context of building/energy retrofit design. The case study of a 2-storey natural gas-heated school building is used to assess whether the reduction of GHG emissions due to savings in operational energy use resulting from the retrofit can offset the impacts of embodied emissions tied to the manufacturing of new envelope and HVAC components. The simulations were conducted for three different locations across Canada, given the relevance of local electricity-grid profile on building's environmental performance outcomes.

1.2 Literature Review

This section introduces the literature review on the topic of life cycle assessment for buildings. Two complementary literature reviews were provided in each of the manuscripts that compose Chapter 2 and Chapter 3 (see sections 2.3 and 3.3). In Chapter 2, the literature review focuses on LCA software tools, low-carbon design, and carbon sequestration potential of greeneries, while in Chapter 3, the focus is on LCA standards, biogenic carbon in wood products, and end-of-life treatment of materials. In order to identify gaps that can potentially impact the LCA outcomes, this section presents practical LCA case studies from existing literature with focus on evaluating their scope and results. These gaps, ranging from LCA methodology to data availability, are key aspects addressed in this thesis.

The following studies have been selected since they are all based on real case studies providing details about design solutions, materials, energy consumption, and energy sources; they present results about life cycle carbon balance, based on LCA calculations, as well as methods, software tools, and databases used for the assessment of carbon emission.

1.2.1 Low Carbon Refugee House (Sweden)

Dabaieh et al. (2019; 2020) assessed the environmental impacts of an experimental 37 m^2 refugee house in Sweden. The first study focused on energy simulations, and the second on the carbon life cycle assessment. Three passive systems were employed to reduce cooling and heating loads, as well as to provide natural ventilation and daylighting: Earth Air Heat Exchanger (EAHE), Trombe Wall, and green wall.

The types of materials applied on the construction include compressed straw panels (load-bearings) covered inside with reeds and clay plasters; wood fiberboards outside, treated with beeswax and linseed oil for waterproofing; roof and floors are made from cross-laminated wood and plywood using air injected wood fibers as insulation. The structure and envelope were made from plant-based materials and the wall design reached U-value of 0.08 $W/m^2.K$.

As presented in Figure 1, the house is equipped with hybrid solar PV and wind power systems, solar water heater (used in summer), and biogas tank using organic waste for cooking and water heating during the winter.

The energy simulation was performed on TRNSYS and ANSYS software, and the results showed that the passive systems helped reducing the heating and loads. The house's energy consumption averaged 180.7 kWh/month (beyond the 240 kWh/month for typical Swedish Standard).

The life cycle assessment was performed using SimaPro and GaBi software for calculation, and the ReCiPe midpoint method for impact assessment**.** The results showed that plant-based materials can drastically reduce the carbon footprint. If the sequestration capacity of plants and plant-based materials are considered, the overall Global Warming Potential (GWP) is -226.2 $kgCO_2eq/m^2$. If it's not considered, the GWP is found to be +254.7 $kgCO_2eq/m^2$.

One limitation of this study is that the embodied impacts associated with manufacturing processes of PV panels and wind turbines were out of the scope, which can potentially impact the LCA results.

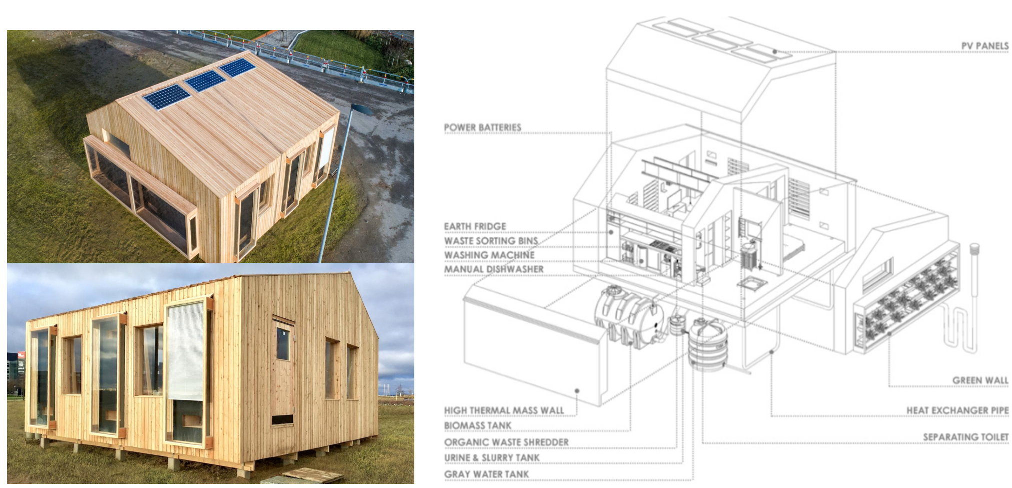


Figure 1. Refugee House in Sweden. Source: Dabaieh, 2019

1.2.2 Mohawk College (Hamilton, Ontario)

This study from Bhavsar et al. (2020) addresses a recently opened educational facility (Figure 2) named Joyce Center for Partnership and Innovation (JCPI Building) on the Mohawk College, located in Hamilton, Ontario. The 8,981 m^2 5-storey building was designed to have an Energy Use Intensity (EUI) of 73 kWh/m^2.year, potentially consuming 80% less energy than the average educational buildings in Ontario. The estimated annual energy demand for the building is 655,613 kWh/year and includes all building end-uses such as electrical and heating loads.

The building was design to generate 100% of its end-use energy demand. Therefore, a set of strategies were adopted, including 8,177 m^2 on-site PV system for electricity generation, geothermal system for heating and cooling (28 geo-exchange wells, each 180 m deep), and solar thermal system for domestic hot water (DHW). Other low carbon solutions included the use of steel with highly recyclable contents, concrete mix with Supplementary Cementing Material (SCM) content (such as slag), 228,000 L cistern for Rainwater Harvesting (RWH) (for non-potable uses), low-flush urinals in toilets, and low flow faucets.

The roofs were designed to have an R-40 thermal resistance (U-value of 0.142 $W/m^2.K$), which is higher than the respective provincial requirement of R-29 (U-value of 0.195 $W/m^2.K$) set in Ontario Building Code. The walls were designed to have an effective R-30 value (U-value of 0.189 $W/m^2.K$). The window consists of two layers: rainscreen and a triple pane glass, with expected R-6.6 value (U-value of 0.860 $W/m^2.K$).

The case study presents a simplified cradle-to-grave LCA, conducted using the software Athena Impact Estimator for Buildings to estimate the building's embodied emissions over a 60-year calculation period. The embodied emissions were estimated only for the building structure, while other carbon-intensive components such as windows, insulation, mechanical equipment, and PV systems were left out of the scope. Overall, the LCA showed that the embodied carbon in the building's structure is about 4,330,000 $kgCO_2eq$.

It is important to note that the embodied emissions would be significantly higher if all building envelope and HVAC components were considered. The use of a 8,177 m^2 PV system in a province where the grid-purchased electricity is mostly based on clean sources was also a gap in this study.

Figure 2. Mohawk College JCPI Building. Source: Bhavsar et al. (2020).

1.2.3 Carbon Neutral Dwelling in Kinmen (Taiwan)

The study by Liu (2019) explored the carbon footprint a building in Kinmen, Taiwan, and it can be seen as relevant benchmark for LCA practitioners, as it addresses a wide range of low carbon design strategies and provides consistent analysis of their carbon emission and offsets.

The results indicated that a zero-carbon dwelling can be achieved through incorporating various sustainable designs and lifestyle modifications. The study uses the Building Carbon Footprint (BCF) evaluation method published by the LCBA in 2013 (available online: https://www.lcba.org.tw/). The BCF method is a result of industrial and academic research in Taiwan, systematic analyses in databases of building materials, building usage, energy statistics during building operation, and carbon footprint estimations.

The energy use intensity (EUI) reported for the building is 33.01 kWh/m^2.year, which is lower than the local EUI average of 49.3 kWh/m^2.year. The design solutions employed in this building included 43 m^2 PV system, wind power, solar hot water system, dual roof design with PV panels and green roof, green areas around the building, reclaimed water (treated in a unique local way with sorghum straw and bacteria, burned oyster shells), infiltration trenches, and LED lighting.

Over 60 years, the carbon footprint of the building was reported as 856,264 kgCO_2eq. The carbon reduction strategies implemented to offset building's life cycle emissions are expected to save 776,673 kgCO_2eq. This value includes 333,223 kgCO_2eq from solar power, 15,780 kgCO_2eq from wind power, 407,100 kgCO_2eq from the dual roof design, 24,990 kgCO_2eq from tree planting, 5,760 kgCO_2eq from LED lighting, and 820 kgCO_2eq from rainwater and wastewater recycling.

Figure 3.Low-Carbon Dwelling in Kinmen. Source: Liu (2019)

1.2.4 Humber College Envelope Retrofit (Toronto, Ontario)

The report by Humber (2019), sourced from the Canadian Green Building Council (CAGBC) portfolio, presents the ZCB-Design certification achieved through the building retrofit project undertaken at Building NX in Toronto, Ontario.

The envelope retrofit included enhanced insulation, airtightness, and triple-pane windows for energy efficiency. Mechanical improvements involved an air-source VRF system, air-sourced heat pumps, and fan-coil units. Lighting was upgraded with sensors for efficiency, and a roof-mounted PV system was installed to generate electricity. It's estimated that the roof PV system will generate approximately 31,500 kWh per year, more than the building will need at certain times of the year. Any excess energy will be fed into the campus central plant, to be used by other buildings.

The 4,487 m^2 5-storey building, was designed to achieve an Energy Use Intensity (EUI) of 63 kWh/m^2.year, potentially leading to a 70% reduction in energy consumption compared to its previous state. The Thermal Energy Demand Intensity (TEDI) was estimated at 12.5 kWh/m^2.year.

Regarding carbon emissions, the report specifically provides data on embodied emissions, quantified at 377.4 $kgCO_2eq/m^2$. These values encompass both new and existing building materials. However, the report does not include details about the assessment's scope and embodied emissions related to the HVAC and PC systems.

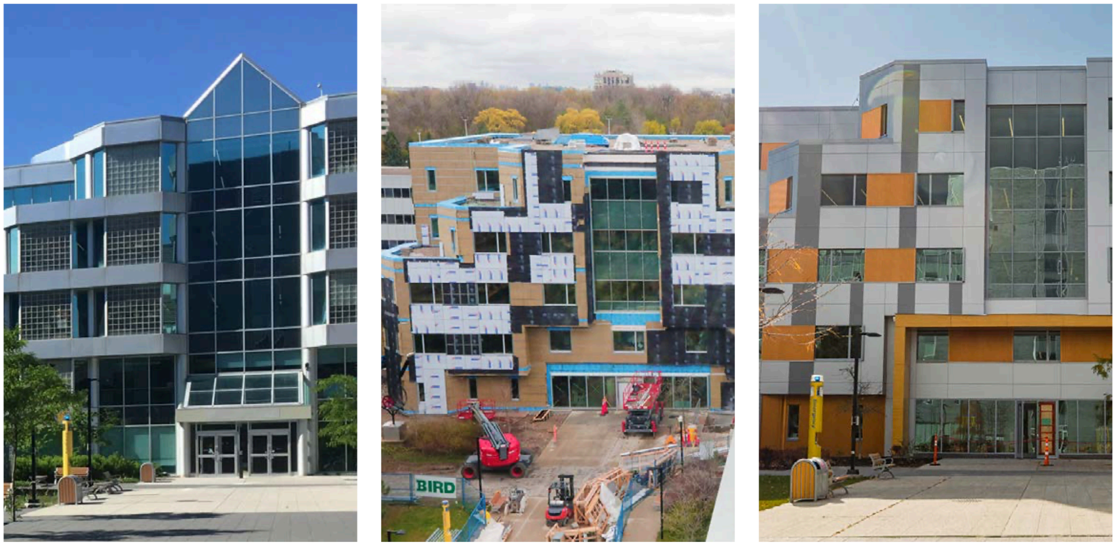


Figure 4. Building NX in different renovation stages. Source: Humber (2019)

1.2.5 Evolv Office Building (Waterloo, Ontario)

Also sourced from the CAGBC portfolio, this case study addresses the Evolv (2018) building, a 3-storey 9,962 m^2 commercial multi-tenant office building located in Waterloo, Ontario, certified under the CAGBC Zero Carbon Building Standard.

It was designed and built to be a net positive energy building incorporating active and passive systems such as high-performance building envelope, open-loop geothermal system using a 160m deep aquifer for heating and cooling, triple pane glazing, solar wall for preheated ventilation, combination of carport and roof-mounted PVs (featuring Canadian-made solar panels) producing 825,014 kWh/year of electricity for the grid, and three-storey green wall, promoting improved indoor air quality. No information regarding carbon sequestration from greeneries is provided. The building was designed to achieve an EUI of 81 kWh/m^2/year, and the TEDI of 24 kWh/m^2/year. The project demonstrated that, on a sunny winter day, Evolv's solar wall is capable of heating the building's fresh air supply enough that it can leave its fresh-air heating system on bypass for significant parts of the day, with a February measurement showing the solar wall was able to heat -13 ºC outdoor air to 16 ºC.

Regarding carbon emissions, the report specifically provides data on embodied emissions, quantified at 260 $kgCO_2eq/m^2$, including only envelope and structure materials, while other materials, HVAC and PVs were left out of the scope.

Figure 5. Evolv Office Building. Source: Evolv (2018)

1.3 Research Needs and Opportunities

Despite the great number of studies addressing building LCA and low-carbon design strategies, there is still no consensus on the large-scale application of carbon neutral building. Most of LCA studies present an incomplete scope, usually neglecting the embodied impacts from mechanical equipment and PV panels. The potential benefits of nature-based solutions, such as the carbon sequestration from tree planting areas around buildings, or the biogenic carbon storage offered by wood products, are usually ignored. Benefits that go beyond the building's life cycle, such as the ones related to end-of-life treatment of materials, are commonly left out of the scope. When addressing building/energy retrofit, the existent LCA studies in the literature rarely account for the environmental impacts associated with the embodied emissions from manufacturing the new materials and equipment employed on the retrofit solution.

The field of environmental impact assessment of buildings presents numerous opportunities for improvement. To address these gaps, we must persist in refining LCA studies, providing consistent benchmarks, and promoting collaborative efforts among researchers, policymakers, and industry professionals. By doing so, we can deepen our understanding of effective design strategies for decarbonization and pave the way for the widespread adoption of Carbon Neutral Buildings.

1.4 Objectives

The objectives of this thesis are:

- To establish a practical and comprehensive cradle-to-cradle LCA framework, based on real case studies, that architects, designers, and engineers may consider when conducting the environmental impact assessment of a building.
- To demonstrate the benefits and viability of implementing nature-based solutions for buildings, as well as pathways for achieving carbon neutrality.
- To provide guidance on calculating and reporting potential carbon offsets associated with carbon sequestration from trees, biogenic carbon content in wood products, and end-of-life treatment of materials.
- To demonstrate the application of the LCA framework in the context of building/energy retrofit and discuss whether the savings in operational emissions resulting from the retrofit can outweigh the impacts of embodied emissions tied to the manufacturing of new envelope and HVAC components.

1.5 Thesis Outline

This manuscript-based thesis consists of 5 chapters:

- Chapter 1: Introduction to the thesis topic, preliminary literature review (further detailed in Chapter 2 and Chapter 3) motivation, objectives, and thesis outline.
- Chapter 2: Manuscript #1, titled "*Feasibility of Planting Trees around Buildings as a Nature-Based Solution of Carbon Sequestration - An LCA Approach Using Two Case Studies*".
- Chapter 3: Manuscript #2, titled *"Life Cycle Assessment of the Environmental Benefits of Using Wood Products and Planting Trees at an All-Electric University Laboratory"*.
- Chapter 4: Application of the LCA framework to the case of building/energy retrofit.
- Chapter 5: Conclusions, main findings, and contributions of this research.

2 Feasibility of Planting Trees around Buildings as a Nature-Based Solution of Carbon Sequestration – An LCA Approach Using Two Case Studies (Manuscript #1)

2.1 Contribution of Authors

This chapter is published in the Buildings journal, by MDPI. It explores the application of an LCA framework through two practical case studies to assess the feasibility of planting trees around buildings as a nature-based solution for carbon sequestration. Felipe Grossi (Master's student and author of this thesis) is the first author of the paper, and has contributed with the formal analysis, data curation, and writing-original draft preparation. Dr. Hua Ge and Dr. Radu Zmeureanu supervised this study and have contributed with the conceptualization, methodology, resources acquisition, editing and review. Dr. Fuad Bada has provided the energy simulation investigation for one of the case studies. All authors have read and agreed to the published version of the manuscript.

2.2 Introduction

It is unequivocal that human activities have contributed to the warming of our planet (Masson-Delmotte et al., 2019). Extreme climate events are becoming more frequent, more intense, and longer lasting all over the world (US-EPA, 2021). There are warning signs in every continent, showing unprecedented and irrefutable evidence that our climate is rapidly changing (Masson-Delmotte et al., 2019).

The Spanish Institute of Health Carlos III (ISCIII) has estimated that there have been 510 deaths attributable to high temperatures within one week in July 2022, during another recent record-breaking heat wave (El País, 2022). With temperatures above 43 °C, 'Zoe' became the world's first heat wave to be officially named by the Seville's new program for the monitoring and ranking of extreme heat waves (ProMETEO, 2022). The same kind of event was experienced by British Columbia, Canada, in late June 2021, leading to 619 heat-related deaths (BCCS, 2022).

In February 2022, multiple floods and landslides ravaged the city of Petropolis, Rio de Janeiro, Brazil, when a heavy rainfall reached 260 mm in less than 3 hours, killing 233 people and leaving a track of destruction all over the city (SFBR, 2022). A similar disaster has also occurred in China's Henan Province, in July 2021. The province's capital, Zhengzhou, recorded a 201.9-mm rainfall within an hour, resulting in floods that submerged entire neighborhoods, trapped passengers in subway cars, caused landslides, and overwhelmed dams and rivers (Reuters, 2021).

Unless society works together to deeply reduce greenhouse gas (GHG) emissions in the coming decades, global warming of 1.5 °C and 2 °C above pre-industrial levels will be exceeded well before the end of the 21st century (Masson-Delmotte et al., 2019), intensifying not only climate events, but also social/migratory issues, as some places might become uninhabitable. In this alarming context, the construction industry can play a critical role in achieving GHG emissions reductions. Currently, buildings are responsible for 39% of global energy related GHG emissions, with 11% due to materials and construction processes (embodied emissions), and 28% due to operational emissions, which include heating, cooling, and general energy use of buildings (WGBC, 2019).

Among the multiple environmental impacts brought about by buildings, energy consumption has always been one of the major concerns. This led many countries to implement new standards for Net-Zero Energy Buildings (US-EPA, 2007; EU, 2010), and boosted the development of different certificate programs addressing energy efficiency, such as Passive House, LEED, and Energy Star.

However, the design and assessment of Net-Zero Energy Buildings commonly focus exclusively on the operational phase, ignoring the environmental impacts of embodied emissions from materials and equipment over the building life cycle (Lützkendorf et al., 2015). Therefore, a new awareness on accounting for whole building life cycle carbon emissions has refocused the construction industry on developing Net-Zero Carbon Buildings (ZCB) (Grinham et al., 2022), also referred to as Carbon Neutral Buildings.

A Net-Zero Carbon Building is a highly efficient building, operated using 100% fossil-free renewable energy, that is designed following best practice sustainable construction (CAGBC, 2022). The term 'best practice sustainable construction' stands for a number of strategies to reduce carbon emissions in buildings, such as promoting energy savings and the wellbeing of occupants through passive design, maximizing the use of recycled and nature-based materials, minimizing energy use in all stages of a building's life cycle, and also creating new green spaces (WGBC, 2021).

At the city level, becoming ‘net-zero’ means exerting zero impact on the environment. Cities like Montreal, New York, Paris, and Toronto have developed action plans, involving the creation of new parks and tree planting areas to recover GHG-absorbing potentials formerly destructed by the built environment (City of Montreal, 2020).

Aligned with environmental commitments set by different countries, this study aims to contribute to the efforts for achieving carbon neutral buildings, by establishing an LCA framework to evaluate the feasibility of using urban trees around buildings as a strategy to sequestrate carbon emissions and offset part of building’s embodied and operational emissions. To demonstrate this approach, the life cycle assessment (LCA) of two real case studies in Montreal were conducted using two LCA software for buildings.

2.3 Literature Review

2.3.1 Keyword Search in Databases

Relevant publications were selected if they contained information on:

- Real case studies, with details about design solutions, materials, energy consumption, and energy sources.
- Results about life cycle carbon balance, based on LCA calculations.
- Methods, software tools, and databases used for the assessment of carbon emission.
- The carbon sequestration potential of vegetation applied to the building context.
- The estimation of annual carbon sequestration rates of trees and vegetation.

The main research databases used in the literature review were Scopus and Elsevier Engineering Village, which has Compendex, Inspec, and GEOBASE subsets, covering all engineering disciplines. Although most publications were selected in the period 2010–2022, some previous studies with relevant information were also included.

The following keywords and terms were used:

Carbon neutral building AND case study; Zero carbon buildings AND case study; Life cycle assessment AND embodied emissions AND operational emissions; Carbon neutral buildings AND carbon sequestration; Carbon sequestration AND vegetation AND buildings; Carbon sequestration AND trees AND buildings; Life cycle assessment AND green roofs.

Since previous studies have not addressed some key aspects, the current paper contributes to the discussion of carbon neutral buildings with the two following items:

- An assessment of the positive impacts of planting urban trees near buildings as a nature-based solution to offset buildings' life cycle embodied and operational GHG emissions, by considering direct carbon sequestration potential;
- A discussion of the quality and completeness of whole building life cycle carbon analysis, with applications for real case studies.

2.3.2 Low-Carbon Design and Vegetation

Progress has been made towards designing and constructing carbon neutral buildings, but there is still no consensus either on their practical large-scale application for achieving carbon neutrality, or on the reliability of available tools for estimating a building's life cycle carbon emissions. Pomponi and Moncaster (2016) reported that most of LCA studies are cradle-to-gate analyses, which disregard what happens with the materials after they leave the manufacturing plants. Some LCA case studies reported only structural and envelope materials in calculations (Bhavsar et al., 2020; Humber, 2019), neglecting the environmental impacts related to the manufacturing of building components such as mechanical systems, photovoltaic (PV) panels, and internal partitions, which have high embodied energy and carbon emissions.

Most of the reviewed papers focus on using on-site solar photovoltaic (PV) electricity production as the main strategy to balance or offset carbon emissions and achieve carbon neturality (Oreskovic et al., 2021; Evolv, 2018; Bhavsar et al., 2020). This positive approach is particularly applicable in regions where grid-purchased electricity is predominantly generated from non-renewable sources, such as the province of Alberta, Canada, where 90% of electricity production relies on coal and natural gas burning (CER, 2021-a). However, for places like Quebec, Canada, where the electricity grid profile is based on hydropower (a clean renewable source) (CER, 2021-b) the positive impacts of solar PVs may not be as significant. This is due to the high environmental "cost" associated with the embodied energy employed in the manufacture of the PVs that are currently commercialized worldwide. Consequently, it is likely that if society achieves a zero-carbon grid in the future, the on-site electricity generated by solar PVs will no longer be able to offset grid emissions, as the grid itself would be already clean (Grinham et al., 2022).

Some projects have been integrating green areas and trees to the design as a way to improve user comfort (Perini et al., 2017; Pan et al., 2018; Cascone et al., 2019). When planted near buildings, trees can indirectly mitigate carbon emissions by moderating the local microclimate, reducing the required amount of energy related to space-cooling in the summer, as well as protecting buildings from strong winds, reducing air infiltration rates and heating loads in winter (Akbari & Konopacki, 2005; Zhao et al., 2010). As shown by Botallico et al. (2016), the urban green infrastructure can contribute to improving urban air quality by abating ozone (O3) and particulate matter (PM10), which are highly detrimental pollutants to human health. Furthermore, the development and conservation of urban forests can also contribute to public well-being by reducing noise pollution and creating a desired soundscape, stimulating for example the pleasantness of perceived birdsongs, as presented in studies by Hong et al. (2021).

However, there is only a small number of papers (Luo et al., 2015; Kuittinen et al., 2016) using LCA to incorporate the direct carbon sequestration potential of greeneries among the strategies to abate part of a building's life cycle CO_2eq emissions. Liu (2019) studied a low-carbon dwelling built on Kinmen, Taiwan, and reported a total reduction of 416.5 kgCO_2eq/year provided by a garden with 481 m² of lawn and 16 units of 20-year-old urban trees (240.5 kgCO_2eq/year from lawn and 176 kgCO_2eq/year from trees). The author based her estimations on studies from Lin et al. (2022) and Lin et al. (2015), which considered the carbon sequestration rates applicable for a period of 40 years. Kuittinen et al. (2016) assessed the life cycle carbon emissions of different buildings in Finland and found that the carbon sequestered in the biomass of shrubs and trees could mitigate around 12% of the total emissions related to a single-detached house. Their approach was based on data from literature, but also included basic field samples, in order to identify the different species of vegetation.

Some papers assessing the annual carbon sequestration rates of particular types of vegetation used in green roofs, living walls, and urban gardens were found in literature for different countries (Heusinger & Weber, 2017; Marchi et al., 2015; Seyedabadi et al., 2021; Leigh et al., 2014; Jo, 2002; Getter et al., 2009; Cai et al., 2019). However, these studies were intended to provide an assessment of the share of the *direct* carbon sequestration contribution on the total life cycle GHG emissions of a specific building (which is the objective of the current paper).

For instance, Heusinger & Weber (2017) measured the CO_2 surface–atmosphere exchange of an unirrigated, extensive green roof composed of sedum species and herbaceous plants over a full annual cycle. They found that the 9 cm-depth green roof was able to sequestrate 0.313 $kgCO_2eq/m^2$ of vegetation per year. Getter et al. (2019) conducted a two-year study on an extensive green roof composed of four different sedum species with a substrate depth of 6 cm. The results after two years showed that the entire system sequestered 1.37 $kgCO_2eq/m^2$, compared with the initial conditions. Luo et al. (2015) assessed the carbon sequestration potential of different irrigated green roofs using a mixed-sewage-sludge substrate (MSSS) over a year. The best configuration in their study was found with a 25 cm-depth MSSS with *Ligustrum vicary* vegetation that resulted in an annual carbon sequestration of 25.8 $kgCO_2eq/m^2$. This high rate of carbon sequestration is due to soil treatment and greater substrate depth. Seyedabadi et al. (2021) implemented a green roof on a four-story building and assessed the performance of different plants in a cold and dry climate by measuring the plant's dry weight biomass increase over one year. They found that the annual carbon sequestration rates ranged from 0.513 $kgCO_2eq/m^2$ to 7.59 $kgCO_2eq/m^2$ of green roof area. Additionally, they estimated through an energy simulation that the green roof could indirectly mitigate up to 28.16 $kgCO_2eq/m^2year$ as a result of an 8.5% reduction of energy consumption.

All these measurements were based on short-time observations, for green roofs aging from 1 to 6 years. After the green roof's vegetation has reached a grown stage, it is very likely that the direct amount of carbon taken in by photosynthesis will just balance out the amount of carbon emitted by the decay of plant material (Sailor & Shon, 2009). Then, to reestablish the carbon sequestration, the vegetation must be replanted.

Different from trees that keep growing for decades, the long-term direct carbon sequestration performance of green roofs is still uncertain (Shafique et al., 2020). In urban areas, trees are stimulated by the increased concentration of CO_2, which provides a fertilizing effect, rendering a more efficient carbon sequestration potential (Fares et al., 2017). Therefore, it seems that urban trees can provide a more reliable and longer-lasting contribution to the achievement of carbon neutral buildings, which doesn't mean that other types of greeneries shouldn't be incorporated to the design of buildings.

2.3.3 Life Cycle Assessment in Canadian Context

Despite the credibility of many available certifications worldwide, and all the efforts from different Green Building Councils on providing standards and design guides for sustainable constructions, there are still some gaps on their approach regarding the scope of LCA calculations.

The most recent version of the Design Standard for Zero Carbon Building (v.03), released by the Canadian Green Building Council in June 2022, only requires for carbon emissions assessment related to structure and envelope materials, and operational energy use (CAGBC, 2022). As a result, important building elements such as internal partitions, finishes, and mechanical/electrical equipment (e.g., HVAC, PV system) have been excluded from the LCA analysis in most of LEED and ZCB-Performance-certified projects. This limitation can lead to an underestimation of 19% to 34% of a project's material-related embodied CO_2 emissions, depending on the type of building (LETI, 2020).

Moreover, the environmental impact assessment of a building can be very sensitive to the assumptions and limitations related to the LCA tool considered for calculations. In North America, Athena Impact Estimator for Buildings and One Click LCA are commonly used software, with regionalized inventory databases for USA and Canada.

Both tools are compliant with ISO 14040/14044 (2006) and EN 15978 (2011) / EN 15804 (2019) standards, and both provide a cradle-to-grave LCA approach (or cradle-to-cradle, if Module D is included), as presented in Table 1.

Table 1. Life cycle stages available in the LCA tools used in current work.

Modules	**Life Cycle Stages**	**Included**
A1–A3	Raw material supply; Transport; Manufacturing	✓
A4	Transport from manufacturing plant to construction site	✓
A5	Construction–installation process (equipment energy use)	✓
B1	Installed product in use	
B2	Maintenance	
B3	Repair [1]	✓
B4–B5	Replacement; Refurbishment (according to materials' service life)	✓
B6	Operational energy use	✓
B7	Operational water use	
C1–C4	De-construction/demolition; Transport; Waste Processing; Disposal	✓
D	Benefits beyond building life (from EOL treatment of materials) [2]	✓

[1] Results for "Repair" could be included manually on One Click (times/year), but are not considered in current work.
[2] Results for "benefits beyond building life" are presented separately.

The main difference is the list of materials available in each software. Athena has a concise inventory, based on common local practice. One Click LCA has a more comprehensive database, including generic and manufacturer-specific material options, based on Environmental Product Declarations (EPDs). The calculations performed by these tools include (i) embodied emissions related to raw material extraction, manufacturing, transportation, use, replacements and disposal, and (ii) operational emissions related to the use of local grid-purchased energy. The benefits beyond a building's life (referred to as 'Module D' on life cycle stages) related to the positive impacts of end-of-life treatment of materials is not mandatory in cradle-to-grave approaches according to EN 15978 (2011), and therefore it is presented separately from other stages.

Athena's inventory database does not provide options for HVAC and PVs, which are items that carry high embodied impacts. For that reason, when necessary, we incorporated One Click's results for those elements into Athena's results.

2.4 Materials and Methods

2.4.1 Overview

This study focuses on the feasibility of planting urban trees around buildings as a nature-based solution to mitigate part of the life cycle carbon emissions related to two real case studies located in Montreal. The environmental impacts (i.e., Global Warming Potential, GWP) of each case study was quantified using two LCA tools commonly used for buildings in North America, One Click LCA (v.0.5.2) and Athena Impact Estimator for Buildings (v.5.4). The values reported for embodied emissions are based on the accumulated radiative forcing under the GWP_{100} perspective, as required by the ISO 21930 (2017), considering a calculation period of 60 years. The carbon sequestration rate of standardized urban trees was estimated based on the studies of Nowak et al. (1994; 2008; 2013) for USA, and Pasher et al. (2014) for Canada. The GWP results related to each case study are presented for different scenarios, before and after considering the direct carbon sequestration potential from urban trees.

Indirect benefits of vegetation (e.g., energy savings) and scenarios including other greeneries (e.g., green roofs, living walls) were out of the main scope of the current paper.

To demonstrate this approach, we performed the carbon LCA of two real buildings in Montreal: a recently constructed all-electric research facility at Concordia University, the Future Buildings Laboratory (FBL); and a single-detached house, natural-gas heated, not energy efficient, built in 1967. The selection of materials in each software was carefully made to best represent the case studies' design specifications, using only locally regionalized data for Canada. A calculation period of 60 years was assumed in LCA calculations, since this is the lifespan considered as the benchmark in EN 15978 (2011). The results provided by each software were compared in terms of life cycle environmental impacts, as well as their background assumptions, calculations, and inventory limitations.

Once the total emissions were estimated for both case studies, we presented the total amount of carbon that could be removed if each case study had their garden area fully covered by representative units of urban trees (410 m² garden at FBL, and 505 m² at the single-detached house). The passive (indirect) effects related to vegetation on moderating local microclimate (by reducing air infiltration, reflecting heat, providing shading, and therefore reducing energy consumption), and other types of greeneries were out of the scope of this paper.

Figure 6 shows the framework developed for this paper, starting with the life cycle assessment of the case studies (resulting in GWP values), followed by the application of carbon sequestration potential of urban trees, leading to a net final carbon balance.

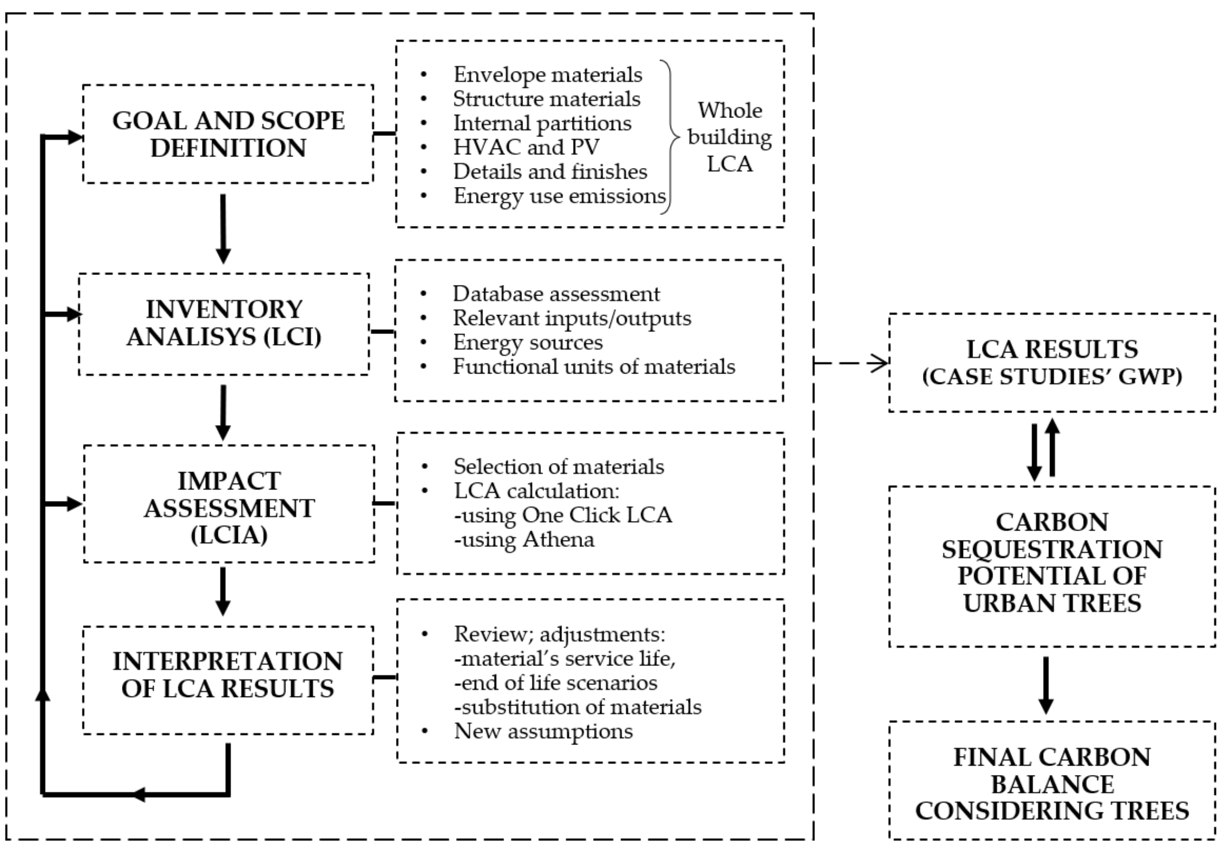


Figure 6. Research framework overview.

2.4.2 Estimation of Building's Environmental Impacts

The impact assessment started with the list of materials for each case study, according to their respective design specifications. This list, organized by building assembly, was mapped within the LCA software where each designed material was linked to an inventory data-point. When necessary, information about thickness, density, and other material properties was also provided. The second input was the annual energy consumption, that was estimated through energy simulation. The GWP results, expressed in $kgCO_2eq$, are presented for each life-cycle stage, considering a 60-year calculation period.

2.4.3 Carbon Sequestration Potential of Urban Trees

This section presents an overview of the estimation of annual carbon sequestration rates of urban trees by Nowak et al. (1994; 2008; 2013) for USA context, and adapted by Pasher et al. (2015) to the Canadian climate. These papers include items such as countrywide conditions, size, and types of urban trees, as concluded into a unique value of annual potential carbon sequestration rate per unit of tree cover area ($kgC/m^2TC.year$). This procedure is followed to estimate the carbon sequestration potential of the garden areas of the two case studies (410 m^2 for FBL, and 505 m^2 for single-detached house) and quantify the maximum offset of the corresponding life cycle emissions.

In the USA context, Nowak et al. (2013) provided field data collection, high resolution photointerpretation, and computer models to determine the country's urban forest structure. Twenty-eight cities in six different states were randomly sampled in plots of 0.04 and 0.067 ha, and each tree inside the sampled boundary was analyzed in terms of species, stem diameter at 1.37m above the ground (DBH), tree cover area, tree height, crown height, crown width, light exposure, leaf area, and crown's general state of life. The tree dry weight biomass for each measured tree (with a minimum size of 2.54 cm diameter at DBH) was calculated using different allometric equations from literature (Tritton & Hornbeck, 1982; Wenger, 1984; Stanek & State, 1978; Clark et al., 1980) as shown by Equations (1) and (2):

$$Y = a \times (DBH)^b \tag{1}$$

$$Y = Exp^{(a+(b \ln DBH))} \tag{2}$$

where Y is the tree biomass (kg dry weight), a and b are regression factors varying with the species and dependent on tree height and age, and DBH is the stem diameter at 1.37 m above the ground. Equations predicting only the aboveground biomass were converted to whole tree biomass based on a root-to-shoot ratio of 0.26 (Cairns et al., 1997). Carbon accounts for approximately 50% of whole tree dry weight biomass (USDA, n/a).

Once the total biomass of each sampled area was calculated, the next step was to estimate how much this biomass would increase in one year. To do that, measured growth rates for street, park, and forest trees from Frelich (1992), De Vries (1987), and Smith and Shifley (1984) were standardized to the length of growing season for each sample location, based on Equation (3):

$$\text{SG} = \frac{\text{measured growth rate} \times 153}{(\text{days of growing season of sample's location})} \quad (3)$$

where SG is the standardized growth rate (cm per year) at the DBH, and 153 days is the minimum length of the growing season (frost-free days) from the measured data—and therefore it was used as the reference length (Nowak et al., 2013). This calculation is made for different species and different growing locations (street, park, forest). For different species of street trees, the average SG was equal to 0.83 cm/year (Nowak et al., 2008).

Then, standardized growth rates (SG) of trees of the same species were compared to determine the average difference between standardized growth rates for street trees (i.e., 0.83 cm/year) and standardized growth for park and forest trees. The difference between a 'street' tree from a 'park' or 'forest' tree is related to the number of sides/top exposed to sunlight: 0–1 sides/top to represent forest growth condition, 2–3 sides/top to represent park tree, 4–5 sides/top to represent street tree. This information is used to calculate the local base growth rates (BG), which is defined in Equation (4):

$$\text{BG} = \begin{cases} \text{SG} \div 2.29 \rightarrow \text{Forest trees} \\ \text{SG} \div 1.78 \rightarrow \text{Park trees} \\ \text{SG} \div 1.00 \rightarrow \text{Street trees} \end{cases} \quad (4)$$

The local base growth rate (BG) is adjusted with Equation (5), according to the trees' state of life condition (which takes into account the color of leaves and other appearance/disease factors) in order to determine the final growth rate. Base growth (BG) rates were multiplied by 1 (no adjustment) for trees in fair to excellent conditions, representing no dieback. For trees in poor conditions, base growth rates were multiplied by 0.62 (26–50% dieback); trees in critical conditions by 0.37 (51–75% dieback); dying trees by 0.13 (76–99% dieback); and dead trees by 0 (100% dieback) (Nowak, et al, 2008).

$$BG_{adjusted} = \begin{cases} BG \times 1.00 \rightarrow \text{fair to excellent conditions (no adjustment)} \\ BG \times 0.62 \rightarrow \text{trees in poor conditions (26 to 50\% dieback)} \\ BG \times 0.37 \rightarrow \text{trees in critical conditions (51 to 75\% dieback)} \\ BG \times 0.13 \rightarrow \text{trees in daying conditions (79 to 99\% dieback)} \\ BG \times 0.00 \rightarrow \text{for those trees that are dead (100\% dieback)} \end{cases} \quad (5)$$

It is important to highlight that SG, local BG, and adjusted local BG are related to growth rates (size increase of tree DBH from year (x) to year (x+1), in centimeters). After estimating the final base growth rates of each tree within each sampled area, it is possible to calculate the increase of biomass from year (x) to year (x+1) for each tree sampled, by using again the biomass equations aforementioned. In a sample level, total biomass of year (x+1) minus total biomass of year (x) is equal to gross annual biomass increase in the sample (Nowak, et al, 2013).

Gross annual increase of biomass is translated to carbon contents, and represents the annual carbon that was sequestrated in each sampled area over one year. The samples' total variation of carbon is divided by the total samples' tree cover area, estimated using photointerpretation and i-Tree methodology (www.itreetools.org/, accessed on 13 August 2022), in order to provide the average gross sequestration rate in units of kgC/m² of tree cover per year.

Once this procedure was applied for all sampled trees, the overall average annual value for USA gross carbon sequestration rate was found to be 0.277 kgC/m² of tree cover, and for net sequestration, 0.205 kgC/m² of tree cover. The net sequestration rate considers the dieback of trees, which incurs GHG emissions due to decomposition of organic matter. Therefore, net sequestration rate averages 74% of the gross sequestration rate (Nowak, et al, 2013). To convert a quantity of carbon (C) into an equivalent quantity of carbon dioxide (CO_2), we multiplied the values of C by 3.67, which represents the ratio of the atomic mass of a CO_2 molecule to the atomic mass of a C atom (44:12) (US-EPA, 2022). The converted values for USA gross and net CO_2 sequestration are 1.015 $kgCO_2eq/m^2TC$ year and 0.751 $kgCO_2eq/m^2TC$ year, respectively.

While a Canadian specific standardized growth rate did not exist, Pasher et al. (2014) assumed that information derived from USA datasets was consistent for Canadian cities, as long as the average value of annual gross carbon sequestration from Nowak (0.277 kgC/m^2TC) was adjusted for a shorter length of growing season in Canada (133 frost-free days). As a result, the annual gross carbon sequestration rate of Canadian urban trees is equal to 0.212 kg C/m^2TC. To calculate net sequestration rates, Pasher et al. (2014) also considered the 74% of gross carbon sequestration from Nowak's works, which resulted in 0.156 kg C/m^2TC year. In terms of CO_2eq, the converted values are 0.777 kgCO_2eq/m^2TC year for gross sequestration and 0.575 kgCO_2eq /m^2TC per year for net sequestration.

In conclusion, a net carbon sequestration potential of 0.575 kgCO_2eq/m^2 of tree cover area per year is used in this paper.

2.4.4 Case Study 1: Future Buildings Laboratory

Opened in 2021, the Future Buildings Laboratory (FBL) is a research facility located at Concordia University's Loyola Campus, in Montreal. The 125 m^2 all-electric lab was designed with a focus on the development of advanced concepts for carbon neutral buildings. The facility is prepared for testing building-integrated photovoltaics (BIPV), motorized shading devices, urban wind energy, and many other technologies. Its envelope incorporates large removable parts, allowing the replacement of approximately 60% of the exterior walls for the assessment of performance of various types of wall assemblies, their hygrothermal performance, effects on indoor environmental conditions, interaction with mechanical systems, and renewable energy.

The building is composed of a concrete slab-on-grade foundation, engineered wood structure made of glued laminated timber, metallic system for the roof, insulated wood frame walls with wood cedar painted cladding, plywood sheathing, insulation, gypsum boards, and finishes. The HVAC system is an air-source heat pump, air-handling unit (with heat recovery), including humidifier and electric heater. Currently the four test cells on the south façade have building-integrated photovoltaic/thermal (BIPV/T) and semi-transparent PV curtain wall systems installed, but the systems have been used just for research purpose, and not yet to generate electricity for the operation of the facility. Thus, its potential to displace carbon emissions from grid-purchased electricity is not considered in this work. Further information about the building is provided in Figure 7, Figure 8 and Figure 9.

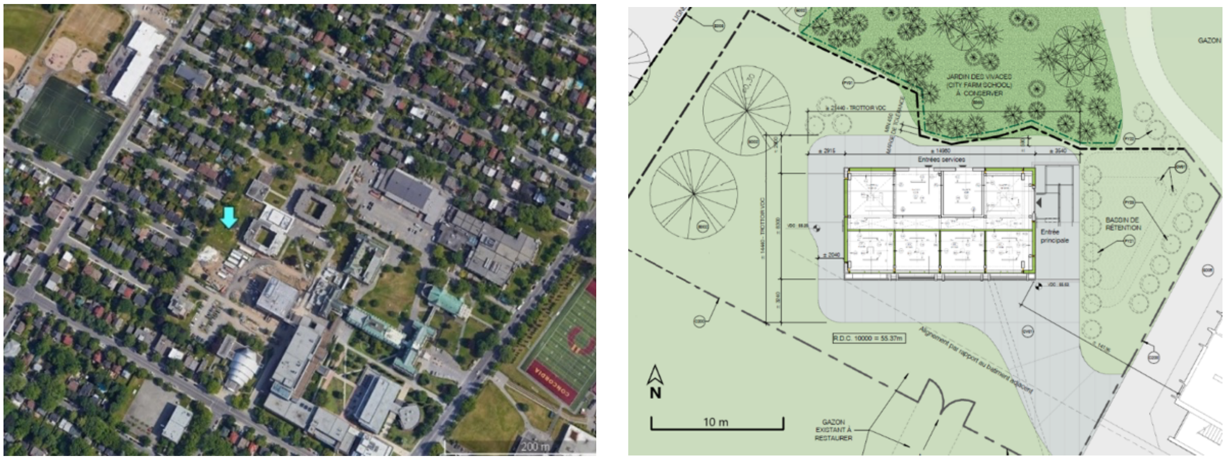


Figure 7. Situation/location plan (left), and landscape boundaries/floor plan (right).

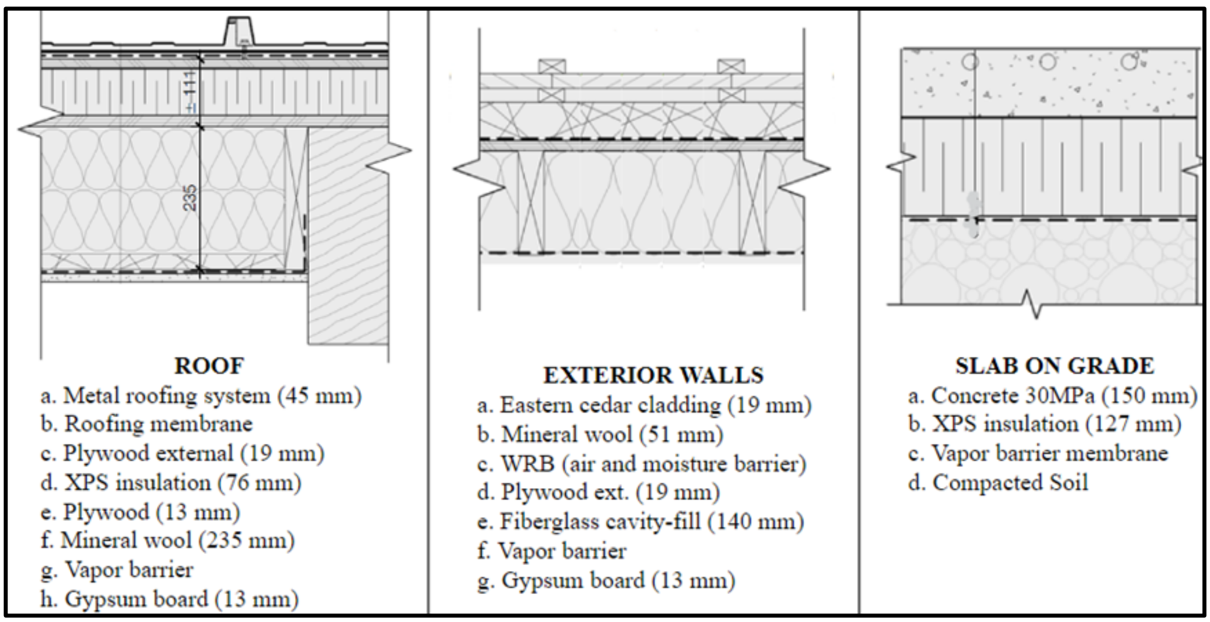


Figure 8. Typical sections of Future Buildings Laboratory envelope assemblies

Figure 9**.** Future Buildings Laboratory in different construction stages

To simulate the annual electricity consumption related to HVAC system, equipment, and interior lighting, the building was modeled in Design Builder (Energy Plus) (v7.0.2.004, 2022) following the design specifications (Table 2 and Table 3).

The simulated annual electricity consumption is 8,868 kWh/year, which is equivalent to 70.94 kWh/m² of heated floor area per year and 11.42 kWh/m³ of heated internal volume per year.

Table 4 lists the bill of materials used in each LCA software for the calculation of environmental impacts related to FBL. The specifications were retrieved from project drawings, and total quantities are related to the construction of the building (software inputs). Additional replacements of materials throughout the buildings' life cycle are automatically calculated by the software based on material's service life defined in these programs, as will be discussed in results section.

Table 2. U-values of the FBL envelope parts.

Building elements	**U-value ($W/m^2.K$)**
Slab-on-grade foundations	0.13
Exterior walls	0.22
Roof	0.14
Windows	1.30
Doors	1.40

Table 3. Energy simulation inputs used on FBL model.

Inputs	**Value**	**Unit**
Occupancy	20.0	m²/person
Lighting power density	5.0	W/m²
Appliances and plug loads	8.0	W/m²
Heating setpoint	22.0	°C
Heating setback	18.0	°C
Cooling setpoint	23.0	°C
Coefficient of performance (summer)	3.5	-
Coefficient of performance (winter)	2.0	-
Ventilation rate (per person)	5.0	L/sec/person
Ventilation rate (per area)	0.9	L/sec/m²
Air change rate (per hour, at 50 Pa)	0.8	ACH

Table 4. Bill of materials of the FBL, and correspondent material option in One Click and Athena.

Project Specification			One Click LCA	Athena
m^3	26.04	Concrete 30 MPa—15 cm slab + borders	Ready-mix concrete, 30 Mpa Industry Average Benchmark (CRMCA)	Concrete Benchmark CAN 30 MPa
kg	1953.6	Steel bars (mesh) d=10 mm, 10 x10 cm	Reinforcement steel (rebar), 7850 kg/m^3 (Gerdau, Whitby plant)	Rebar, Rod, Light Sections
m^2	198.40	Insulation, RSI-3.42, rigid, XPS, 127 mm	XPS insulation, 15 psi, R-10, 50.8 mm, Foamular XPS (Owens Corning)	Extruded Polystyrene
m^2	156.75	Insulation, RSI-2.59, rigid, XPS, 76 mm		
m^2	197.90	Insulation, RSI-4.29 cavity fill, FG, 140 mm	Glass wool insulation panels, unfaced, generic, L = 0.031 W/mK, R = 3.23 m2 K/W	FG LF Cavity Fill R22
m^2	197.90	Insulation, RSI-1.41, semi-rigid, MW, 51 mm	Rock wool insulation board, R=8.6, 50.8 mm, 88 kg/m2, (Rockboard 60)	MW Batt R11-15
m^2	119.22	Insulation, RSI-1.41, semi-rigid, MW, 89 mm		
m^2	156.75	Insulation, RSI-5.64, semi-rigid, MW, 235 mm	Mineral fiber batt insulation, 6.89 in	MW Batt R30
m^2	124.10	Gypsum board, fire resistant, 13 mm	Glass-mat gypsum boards, fire/moisture., 12.7 mm, 10.15 kg/m2 (AGC)	1/2″ Fire- Type X Gypsum Board
m^2	395.19	Gypsum board, regular, 13 mm	Gypsum plaster board, regular, generic, 6.5–25 mm, 10.725 kg/m2 for 12.5 mm	1/2″ Regular Gypsum Board
m^2	400.89	Gypsum board, fiber-board, 16 mm	Gypsum plaster board, regular, generic, 6.5–25 mm, 10.725 kg/m2 for 12.5 mm	5/8″ Gypsum Fibre Gypsum Board
m^2	197.90	Plywood board, 13 mm	Softwood plywood, 477.33 kg/m^3 (Canadian Wood Council)	Softwood Plywood
m^2	156.75	Plywood board, external, 19 mm	Softwood plywood, 709.79 kg/m^3 (American/Can. Wood Council)	
m^2	23.12	Plywood board, 19 mm	Softwood plywood, 477.33 kg/m^3 (Canadian Wood Council)	
m^3	16.33	Glued Laminated Timber	Glue laminated timber (Glulam), 467.3 kg/m^3 (Canadian Wood Council)	GluLam Sections
m^3	8.16	Wood joists, glulam, 5 × 25 cm, 300 mm sp	I-joist, wood (FPInnovations)	
m^3	1.34	Wood joints cover for cladding, 2 × 4 cm	Softwood lumber, kiln-dried, 19 mm, 460 kg/m^3 (Can. Wood Council)	Small Dim. Softwood Lumb, kiln-dried
m^3	6.84	Wood studs, 5 × 20 cm, 400 mm spacing		
m^2	197.90	Eastern cedar cladding, painted, 19 mm	Western red cedar bevel siding, painted, 1 × 6 in (W Red Cedar Lumber Assoc.)	Cedar Wood Shiplap Siding
m^2	532.34	Air/water barrier 6 mil	Air and water barrier system, mechanically fastened, 0.11 kg/m2, Tyvek (DuPont)	Air Barrier
m^2	396.65	Vapor barrier, dynamic, 6 mil		Polypropylene Scrim Kraft Vap. Ret.
m^2	156.75	Metal roofing syst (45 mm w/membrane)	Hot-dip galvanized steel sheets, 0.4–3.0 mm, zinc coating, 0.28 kg/m2	Metal Roof Cladding—Resident. 30
m^2	156.75	Impermeable membrane (roof)	SPPR PVC roofing membrane, single-ply, 40 mil (Chemic.Fab. Film Assoc.)	#30 Organic Felt
kg	200.00	Bolts, Fasteners, Clips	Structural steel profiles, generic, 40% recycled content	Bolts, Fasteners, Clips
m^2	26.00	Windows aluminum frame	Aluminum frame windows, 37 kg/m^2—30% Alum., 61% Glazing (AluQuébec)	Aluminum Window Frame
m^2	26.00	Double Glazed Hard Coated Argon		Double Glazed Hard Coated Argon
m^3	0.20	Doors/steel doors	Galvanized steel door w/ polystyrene, 44.5 mm, 41 kg/unit (De La Fontaine)	Rough Lumber SFWP
m	75.00	Steel structure on roof to support BIPV/T	Stainless steel crash rails with tube brackets, 10.84 kg/m (Constr.Specialties)	Steel Tubing

m^2	120.00	Industrial floor paint—Epoxy or similar	Water-based epoxy floor and wall coating, 2.31 kg/m^2 (SherWilliams)	Solvent Based Alkyd Paint
				Solvent Based Varnish
m^2	698.31	Paint intern	Recycled latex paints, interior, 12 m2/L, 1.23 kg/L, 0.205 kg/m2, (Laurentide)	Water Based Latex Paint
m^2	23.12	Vinyl cover, 27pprox. 3 mm	Vinyl tile flooring, 2.4–3.2 mm, 6.4–6.9 kg/m^2 (Armstrong, Tarkett)	Vinyl Siding
unit	1.00	HVAC (air src heat pump, 2.5 kW output, 47.5 MJ/h) + air handling unit	Ground source heat pump (excluding ground tubes), per 1 kW max output	N/A—One Click's results adopted
			Air hand. Unit, w/ heat recovery, indirect liq. Circulation, 1000 m^3/h, 92 kg/unit	N/A—One Click's results adopted
m^2	15.00	PV system 1.63 kWp (BIPV on south façade)	PV polycrystalline panel, per m2, 210 Wp (One Click LCA)	N/A—One Click's results adopted

Obs.: For insulation materials, software' default thicknesses (provided in terms of functional unit) were adjusted to match the R-values defined in project specifications

2.4.5 Case Study 2: Single-Detached House

The second case study is a single-detached house built in 1967, not energy-efficient, located in Dollard-des-Ormeaux (near Montreal). The information about the house was retrieved from Baouendi (2003). The house has 258 m^2 of heated floor area and encompasses 14 rooms that are distributed on one main floor and a basement. It has a typical wood frame envelope, with brick veneer in the above ground exterior walls, reinforced concrete in the basement walls and foundations and double-glazed aluminum frame windows. The annual energy consumption was simulated using the HOT2000 software (Baouendi, 2003). Natural gas is used for space heating and domestic hot water (DHW) (3,561.3 m^3, equivalent to 13.8 m^3 gas/m^2.year), and electricity is used for lighting and electric appliances (9,725 kWh, equivalent to 37.7 kWh/m^2.year). No air conditioning is used. The basic simulation inputs are presented in Table 5 and Table 6.

Table 5. U-values of the single-detached house envelope parts.

Envelope Assemblies	**U-Value (W/m².K)**
Basement floor	1.00
Basement walls	0.48
Above ground walls	0.45
Roof and ceiling	0.18
Windows	2.97
Doors	1.80

Table 6**.** Energy simulation inputs of the single-detached house.

Energy Simulation Inputs	**Value**	**Unit**
Occupancy	60.0	m^2/person
Temperature setpoint for heating	19.0	°C
Temperature domestic hot water	55.0	°C
Forced-air natural gas furnace heating	80	MJ/h
Volumetric air flow rate	210.0	L/s
Air change rate (measured, at 50 Pa)	7.76	ACH

In order to highlight the high environmental impact of natural gas, an alternative setup was proposed by converting the energy provided by natural gas to an energy equivalent value of electricity. 1 m^3 of natural gas is equivalent to 10.73 kWh (NRC, 2015). Thus, for this alternative setup, the total electricity consumption (general use, plus heating and DHW) is 47,950 kWh/year (equivalent to 185 kWh/m^2/year).

The garden area of 505 m² represents the typical landscape of single-detached houses in Dollard-des-Ormeuax, as shown in Figure 10. The bill of materials inputted in the LCA softwares to calculate the life cycle GWP is presented in Table 7.

Figure 10. Typical landscape and garden of single-detached house in Dollard-des-Ormeaux.

Table 7. Bill of materials of the single-detached house, and correspondent material option in One Click and Athena.

Project Specification			One Click LCA	Athena
m3	36.77	Concrete 30 Mpa	Ready-mix concrete, 30 MPa Industry Average Benchmark (CRMCA)	Concrete Benchmark CAN 30 MPa
kg	3991.24	Steel rebars (double mesh)	Reinforcement steel (rebar), generic, 80% recycled content, A615	Rebar, Rod, Light Sections
m3	12.55	Brick veneer, 10.9 mm thickness	Clay brick, 2120 kg/m3 (several manufacturers)	Ontario (Standard) Brick
m3	3.46	Mortar (0.03 m³ per m² of brickwork)	Lightweight mortar, single component, 3.625 kg/m2 (Mapei)	Mortar
m2	107.62	Insulation RSI-4.94, FG, cavity fill, 89 mm	Insulation, glass wool, loose, 30 m2 K/W, Industry average US (NAIMA)	FG LF Cavity Fill R30
m2	137.55	Insulation RSI-3.53, FG, cavity fill, 152 mm	Glass wool insulation panels, unfaced, generic, L = 0.031 W/mK, R = 3.23 m2 K/W	FG LF Open Blow R13-20
m2	137.55	Insulation RSI-3.53 FG, continuous, 152 mm		
m2	958.57	Gypsum board, 13 mm	Gypsum plaster board, regular, generic, 12.5 mm, 10.725 kg/m2	1/2″ Regular Gypsum Board
m2	594.63	Plywood board, 13 mm	Softwood plywood, 477.33 kg/m3 (Canadian Wood Council)	Softwood Plywood
m2	497.88	Polyethylene sheet, 6 mil	PVC-polyester waterproofing membrane (Chemical Fabrics and Film Association)	6 mil Polyethylene
m2	275.10	Wood flooring	Solid hardwood flooring, 19 mm, 12.35 kg/m2 (Wickham)	Spruce Wood tongue/groove (closest option)

m3	6.88	Wood studs 5 × 15 cm	Softwood lumber, kiln-dried, 460 kg/m3, (Canadian Wood Council)	Small Dimension Softwood Lumber, kiln-dried
m3	8.80	Wood studs 5 × 10 cm		
m3	1.70	Wood joists 5 × 10 cm		GluLam Sections
m3	0.76	Wood Doors	Hardwood lumber (Quebec Wood Export Bureau)	Rough Lumber SFWP
m2	17.00	Windows aluminum frame	Aluminum frame windows, 37 kg/m2, 30% Alum., 61% Glazing (AluQuébec)	Aluminum Window Frame
m2	17.00	Double glazed units		Double Glazed Soft Coated Air
m2	958.56	Paint intern	Recycled latex paints, interior, colored, 0.205 kg/m2 (Laurentide re/sources)	Water Based Latex Paint
m2	204.36	Asphalt shingle	Fiberglass asphalt shingle roofing system, 12.7 kg/m2 (ARMA)	Organic Felt shingles 30 yr
m2	204.36	Organic felt	SPPR PVC roofing membrane, 60 mil (Chemical Fabrics and Film Association)	6 mil Polyethylene
kg	200.00	Bolts, Fasteners, Clips	Structural steel profiles, generic, 40% recycled content, I, H, U, L, and T sections	Bolts, Fasteners, Clips
unit	1.00	HVAC (forced-air nat gas furnace, 80 MJ/h)	Air handling unit, w/ heat recovery, liquid circulation, 1000 m3/h, 92 kg/unit	N/A—One Click results adopted

Obs.: For insulation materials, software' default thicknesses (provided in terms of functional unit) were adjusted to match the R-values defined in project specifications

2.5 Results and Discussion

2.5.1 LCA Results: Future Buildings Laboratory

The life cycle CO_2eq emissions for the FBL are presented in Table 8, as obtained from the two software, One Click LCA and Athena Impact Estimator, considering a 60-years calculation period using the GWP_{100} perspective. The baseline scenario considers all life cycle stages (A1–A5, B4–B6, C1–C4), except for module D (benefits from end-of-life treatment of materials). For the baseline scenario, the total GWP, without considering the carbon sequestration potential of trees, is equal to 83,521 kgCO_2eq (calculated using One Click LCA) and 82,666 kgCO_2eq (using Athena). The share of emissions from each life cycle stage for this scenario is presented in Figure 11. In terms of annual CO_2eq emissions per heated floor area (125 m^2), the results are 11.13 kgCO_2eq/m^2 (using One Click) and 11.02 kgCO_2eq/m^2 (using Athena).

The second scenario includes module D, which is not mandatory in the cradle-to-grave approach according to EN 15978 (2019). The GWP estimated for this scenario, without vegetation contribution, is equal to 47,363 kgCO_2eq (calculated using One Click LCA) and 55,112 kgCO_2eq (using Athena). In terms of annual CO_2eq emissions per heated floor area, the results are 6.31 kgCO_2eq/m^2 (using One Click LCA) and 7.34 kgCO_2eq/m^2 (using Athena).

Table 8. LCA results for Future Buildings Laboratory: Global warming potential (without contribution of trees).

Modules	**Life Cycle Stages**	**One Click LCA (kgCO_2eq over 60 yr)**	**Athena (kgCO_2eq over 60 yr)**
A1–A3	Material manufacturing processes	55,715	51,692
A4	Transportation to site	2,131	1,793
A5	Construction process	2,633	1,647
B4–B5	Replacement; Refurbishment	14,282	14,320
B6	Operational energy use	5,445	9,737
C1–C4	End-of-life (demolition; disposal; waste processing)	3,313	3,473
D	Benefits beyond building's life (from EOL treatment of materials)	−35,885	−27,553
Scenario 1	**Total Emissions—Modules A to C—baseline scenario**	**83,521 (11.13)**	**82,666 (11.02)**
Scenario 2	**Total Emissions—Modules A to D**	**47,636 (6.31)**	**55,112 (7.34)**

Obs. 1: HVAC and PV are not available in Athena database. Thus, for these two items, the values from One Click were considered for Athena.
Obs. 2: Values between parenthesis (e.g., (9,28)) refers to the equivalent CO_2eq emissions results per m^2 of heated floor area per year.

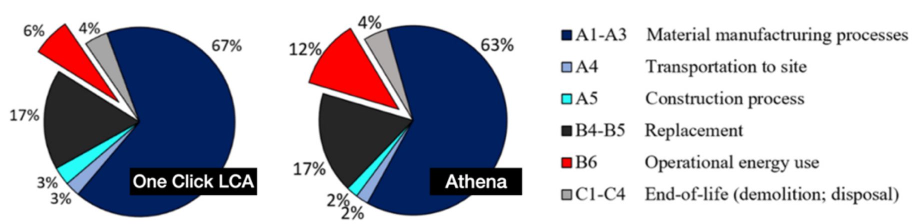


Figure 11. Emissions contribution of each life cycle stage for FBL baseline scenario (A to C), One Click and Athena.

There are a few aspects related to software calculations and material inventory options that need to be discussed regarding the Future Buildings Laboratory's LCA results:

- **(1)** Although the operational emissions (module B6) are only dependent on two inputs (building location and annual energy consumption by type of fuel), the result provided by Athena for this module (9,737 kgCO2eq) is almost 80% higher than the results from One Click LCA (5,445 kgCO2eq). The reason is that Athena contains highly specific data for North American regions, which means that city-level geographic relevance is critical, especially for operational emissions. According to Athena's Transparency Document (2019) and customer support service, starting with version v.5.4, the source data for electricity profiles for Canadian provinces has been changed to Ecoinvent 3.4-2017, which is very likely to include factors for biogenic decay in hydro reservoirs (rotting vegetation emitting CO2 and methane (CH4)), and other impacts related to transmission processes, which results in a multiplier factor of 0.018302 kgCO2eq per kWh. For One Click LCA, the operational electricity use emissions are calculated considering a factor of 0.010234 kgCO2eq per kWh of electricity. Based on the information presented from reading data-cards available in the One Click LCA browser, the calculation is done according to an internally verified LCA study for country-specific electricity mixes (Quebec/Canada) based on the International Energy Agency (IEA), StatCan (2020) and Ecoinvent databases from 2020.
- **(2)** There is a high environmental impact due to the use of Extruded Polystyrene (XPS) insulation materials, which is the type of insulation specified for the FBL's foundation and roof. The impact of XPS exceeds any other materials, carrying a GWP of around 20,700 kgCO2eq over 60 years, which represents 25% of the total life cycle emissions for the baseline scenario (modules A to C). Both software use data from publicly available Environmental Product Declarations (EPDs) from Owens Corning and Dupont to estimate life cycle CO2eq emissions impacts. The raw material extraction and manufacturing processes of XPS are the main contributing modules, including emissions from electricity, natural gas and liquefied petroleum gas combustion, as well as blowing agent emissions from the trimming, cutting, and profiling of the XPS boards. The chart presented in Figure

12 was adapted from One Click LCA to demonstrate the total GWP contribution related to the most impactful materials considered in this case study.

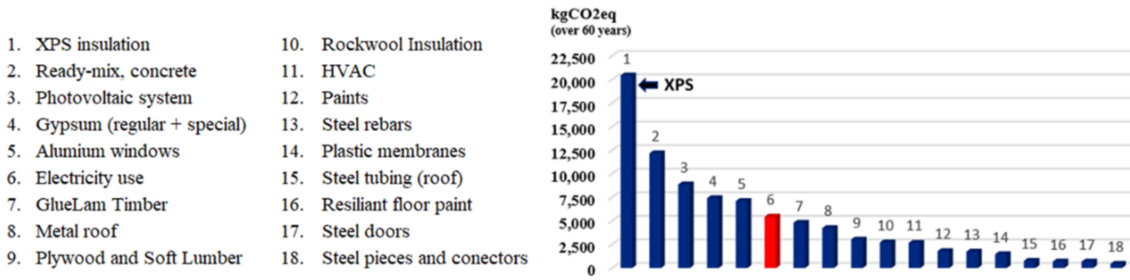


Figure 12. Life Cycle GWP contribution by material type (and energy use, in red), for baseline scenario, based on One Click LCA.

- **(3)** The life cycle stage "replacement; refurbishment" (modules B4/B5) also represents a relevant burden on the final LCA results. It contributes around 14,300 kgCO_2eq, representing 17% of the FBL's emissions, calculated using both software. The service life determines how long the product is in use before it is replaced. Foundation materials, for example, are never replaced. Insulation materials usually have a service life of 75 years, as defined in different EPDs, which is longer than the 60-years' service life assumed for the case studies in this paper. Equipment such as HVAC and PV have a shorter service life (20 to 25 year); taking the 15 m^2 PVs as example, it carries embodied emission of around 3,000 kgCO_2eq due to manufacturing processes (A1-A5), and 6,000 kgCO_2eq more due to two events of replacement (at building age of 20 years and 40 years).
- **(4)** Default scenarios are assumed for end-of-life stages. The default inputs are based on the processing chain defined in EPDs, or local common practice. In One Click LCA, it is possible to alternate those scenarios that impact the results for modules C2 to C4, and also for module D, if applicable. Examples of end-of-life treatments are landfill (for inert materials), wood incineration, plastic-based material incineration, steel recycling, gypsum recycling, and glass-containing and metal-containing product recycling.

2.5.2 LCA Results: Single-Detached House

Following the same approach adopted in the first case study, the baseline scenario for the single-detached house also considers a 60-years calculation period, and includes all life cycle stages, except for module D. As presented in Table 9, the total GWP calculated using One Click LCA is equal to 544,907 kgCO_2eq, and using Athena is equal to 566,856 kgCO_2eq. In terms of annual CO_2eq emissions per heated floor area (258 m²), the results are 35.2 kgCO_2eq/m² (using One Click LCA) and 36.62 kgCO_2eq/m² (using Athena).

The second scenario includes module D, benefits beyond a building's life, which brings benefits from end-of-life treatment of materials. For this scenario, the GWP results are 518,823 kgCO_2eq with One Click LCA, and 541,119 kgCO_2eq with Athena. In terms of annual CO_2eq emissions per heated floor area, the results are 33.51 kgCO_2eq/m² (using One Click LCA) and 34.95 kgCO_2eq/m² (using Athena).

This case study house uses natural gas for heating and domestic hot water supply, which results in a high GWP related to the operational use stage (module B6), accounting for about 90% of total LCA carbon emissions, as shown in Figure 13. If we consider a gas-free setup (scenario 3, A to C), where the natural gas has been converted to an energy equivalent value for electricity, the house's total life cycle GWP calculated using One Click LCA results in 82,456 kgCO_2eq (5.32 kgCO_2eq/m².year), and using Athena, it results in 95,697 kgCO_2eq (6.18 kgCO_2eq/m².year).

Table 9. LCA results for the single-detached house: Global warming potential (without contribution of trees).

Modules	Life Cycle Stages	One Click LCA kgCO_2eq over 60yr	Athena kgCO_2eq over 60yr
A1–A3	Material manufacturing processes	36,404	28,419
A4	Transportation to site	2845	2142
A5	Construction process	1968	1213
B4–B5	Replacement; Refurbishment	9812	9378
B6	Operational energy use	491,894 / 29,443 *	523,812 / 52,654 *
C1–C4	End-of-life (demolition; disposal; waste processing)	1981	1889
D	Benefits beyond building life (end-of-life treatment benefits)	−26,084	−25,736
Scenario 1	**Total Emissions (Modules A to C)—baseline scenario**	**544,907 (35.20)**	**566,856 (36.62)**
Scenario 2	**Total Emissions (Modules A to D)**	**518,823 (33.51)**	**541,119 (34.95)**
Scenario 3	**Total Emissions (Modules A to C)—natural gas converted to electricity**	**82,456 (5.32)**	**95,697 (6.18)**

* Emissions from module B6 (operational energy use) considering the setup where natural gas was converted to electricity.
Obs. 1: HVAC and Boiler are not available in Athena's database. Thus, for these two items, the values from One Click LCA were considered for Athena; Obs. 2: Values between parenthesis (e.g., (35.20)) refers to the equivalent CO_2eq emissions results per m² of heated floor area per year.

Regarding the individual result of module B6 (operational energy use emissions) for this gas-free scenario, it drops from 491,894 kgCO_2eq to 29,443 kgCO_2eq (One Click LCA), and from

523,812 $kgCO_2eq$ to 52,654 $kgCO_2eq$ (Athena). Table 10 presents information about the calculation of operational emissions, and Figure 13 presents a comparison between the share of embodied and operational emissions for this situation.

Table 10. Energy consumption and operational emissions for the Single-detached house (scenarios #1 and #3).

REAL SCENARIO 1 (electricity + natural gas)	Energy Consumption (Annual)	One Click LCA $kgCO_2eq$ over 60yr	Athena $kgCO_2eq$ over 60yr
Electricity (general use)	9,725 kWh/year	5,971	10,679
Natural gas (for space heating and DHW)	3,561.3 m3/year	485,923	513,133
Total Operational Emissions (module B6)		**491,894**	**523,812**
SCENARIO 3 (natural gas converted to electricity)			
Electricity (general use)	9,725 kWh/year	5,971	10,679
Electricity (heating and DHW, converted from nat. gas)	38,225 kWh/year	23,472	41,975
Total Operational Emissions (module B6)		**29,443**	**52,654**

Obs. 1: Equivalent CO_2 emissions per kWh from electricity: 0.010234 $kgCO_2eq$/kWh (One Click) and 0.018302 $kgCO_2eq$/kWh (Athena)
Obs. 2: Equivalent CO_2 emissions per kWh from natural gas: 0.211869 $kgCO_2eq$/kWh (One Click) and 0.223734 $kgCO_2eq$/kWh (Athena)

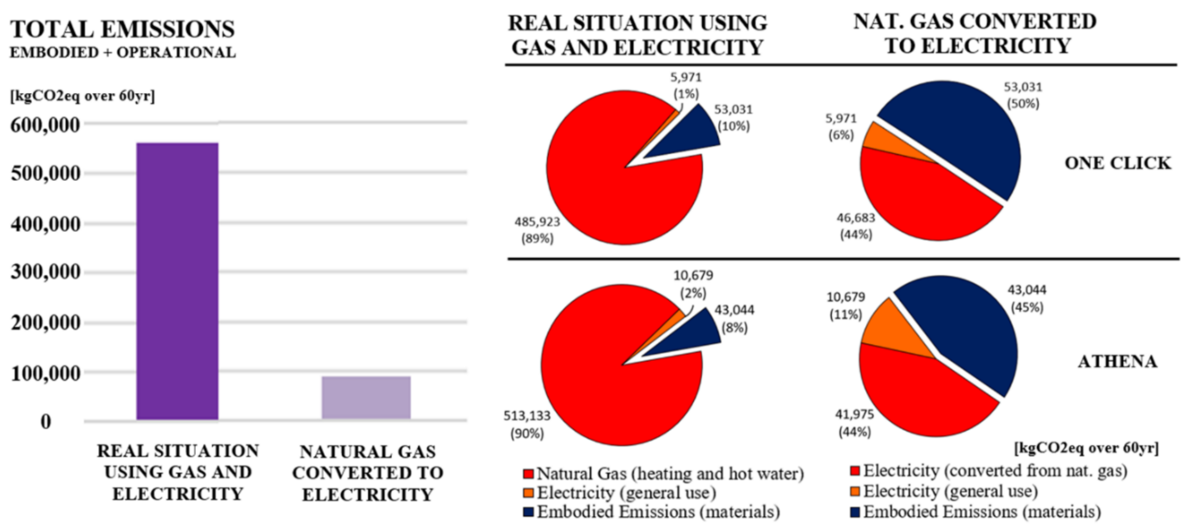


Figure 13. Comparison between real situation (scenario 1) and gas-free (scenario 3) for the single-detached house.

This situation illustrates the importance of shifting to all-electric buildings in places like Quebec, Canada, where the electricity grid is based on renewable sources (i.e., hydro power). In Table 10, if we divide the total life cycle operational emissions related to the use of natural gas in the real scenario 01 by its equivalent (converted) value of electricity consumption in the gas-free scenario 03 (38,225 kWh/year, over 60 years), the results are around 0.211 $kgCO_2eq$/kWh consumed (with One Click), and 0.223 $kgCO_2eq$/kWh with Athena. Those values are 10 to 20 times higher than the CO_2eq emissions per kWh from electricity, which are equal to around 0.0102 $kgCO_2eq$/kWh (One Click) and 0.0183 $kgCO_2$/kWh (Athena) in the case of Montreal.

2.5.3 Final Balance: Potential for Carbon Sequestration Using Trees

Until this point, the results provided and discussed were all about the LCA calculations, which did not include the potential of tree planting areas around the case study buildings to sequestrate CO_2 and reduce their carbon footprints.

The final balance is the difference between the total life cycle CO_2eq emissions related to each building and the total CO_2eq captured by the trees in their respective gardens. If we consider that the garden areas (410 m^2 for the FBL, and 505 m^2 for the single-detached house) are fully covered by representative urban trees without canopy overlap, then the carbon sequestration potential at the FBL is equal to 235.7 kgCO_2eq/year (annual sequestration rate of 0.575 kgCO_2eq/m^2 of tree cover area multiplied by 410 m^2 garden area), and at the single-detached house is 290.3 kgCO_2eq/year (0.575 kgCO_2/m^2TC multiplied by 505 m^2 garden area).

Supposing that the annual sequestration rates from these trees will remain constant during the 60-years calculation period (which is a reasonable assumption, since the sequestration rate estimation encompasses different trees under different growing stages), the life cycle carbon sequestration potential of these gardens is equal to 14,145 kgCO_2eq for the FBL, and 17,418 kgCO_2eq for the single-detached house (Table 11).

In the case of the FBL's baseline scenario 01 (modules A to C), the final balance resulted in 69,377 kgCO_2eq (One Click) and 68,521 kgCO_2eq (Athena). Therefore, this set of representative urban trees has the potential to offset 16.9% and 17.1% of the FBL's total life cycle emissions calculated using One Click LCA and Athena, respectively.

When we apply those potentials to the baseline scenario of the single-detached house (which has natural gas as part of its energy source), the CO_2 removals from the trees can offset only 3.2% of the total emissions (One Click LCA), and 3.1% (Athena). However, if we consider the alternative setup for the single-detached house (scenario 03) where natural gas is converted to an energy equivalent value of electricity, the carbon removals from the trees would have the potential to offset 21.1% of the total emissions (One Click LCA results), and 18.2% for Athena.

The results for those and other scenarios are presented in Table 11.

Table 11. Summary of results and contribution of trees on reducing buildings' life cycle carbon emissions.

	Total Emissions (without trees) kgCO2eq over 60yr		**Total CO_2 Sequestration*** kgCO2eq		**Final Carbon Balance (with trees)** kgCO2eq over 60yr		**Trees contribution** [%]	
	OneClick	Athena	per year	over 60y	One Click	Athena	One Click	Athena
FUTURE BUILDINGS LAB								
Scenario 01 (A to C) - baseline	83,522	82,666	235.7	14,145	**69,377**	**68,521**	16.9%	17.1%
Scenario 02 (A to D)	47,636	55,112			**33,491**	**40,968**	29.7%	25.7%
SINGLE-DETACHED HOUSE								
Scenario 01 (A to C) - baseline	544,907	566,856	290.3	17,418	**527,489**	**549,438**	3.2%	3.1%
Scenario 02 (A to D)	518,823	541,120			**501,405**	**523,702**	3.4%	3.2%
Scenario 03 (A to C) - gas-free	82,456	95,698			**65,038**	**78,280**	21.1%	18.2%

*Calculated using annual CO_2 sequestration rate of 0.575 $kgCO_2eq/m^2TC$, garden areas of 410 m^2 (FBL) and 505 m^2 (Single-detached house), and 60-year time-horizon.

Alternatively, in an additional scenario where only the operational use stage is considered (module B6), the relative contribution provided by the trees would be much more effective if applied to cases of all-electric buildings than to natural gas-heated buildings. For places like Quebec, with the energy grid generation based on renewable sources, it would be feasible to achieve carbon neutral operational use stage by including the trees around buildings, since the operational emissions are low.

As shown in Table 12, in the FBL, the operational use stage is responsible for 5,445 $kgCO_2eq$ emissions (calculated using One Click) and 9,737 $kgCO_2eq$ (using Athena), while the total potential of the trees to sequestrate carbon is 14,145 $kgCO_2eq$. Therefore, carbon neutrality of the operational use stage would be achieved, resulting in a balance equal to –8,700 $kgCO_2eq$ (One Click) and –4,408 $kgCO_2eq$ (Athena).

Table 12. Carbon balance considering only operational use stage.

	Operational Emissions (module B6) kgCO2eq over 60yr		**Total CO_2 Sequestration** kgCO2eq over 60yr	**Carbon Balance (operational stage)** net kgCO2eq		**Trees contribution** [%]	
	One Click	Athena	From trees	One Click	Athena	One Click	Athena
Future Buildings Laboratory	5,445	9,737	14,145	**–8,700**	**–4,408**	260%	145%
Single-detached House*	29,443	52,654	17,418	**12,025**	**35,236**	59%	33%

*Considering the scenario where natural gas has been converted to energy equivalent value of electricity.

For the single-detached house (gas-free scenario), the operational use stage is responsible for 29,443 $kgCO_2eq$ emissions (One Click) and 52,654 $kgCO_2eq$ (Athena), while the total carbon sequestration potential due to the garden full of trees is 17,418 $kgCO_2eq$. Therefore, the balance would be 12,025 $kgCO_2eq$ (One Click) and 35,235 $kgCO_2eq$ (Athena).

Although this is not enough to offset 100% of the operational use stage emissions, it can contribute towards reducing 59% and 33% of operational emissions, considering One Click and Athena's results. It is important to remember that the FBL is a state-of-the-art construction, projected with a focus on energy performance, while the single-detached house is a typical construction from the 1960s with several issues of air leakage.

Although it might not be possible to reach a net-zero carbon balance by just considering the direct carbon sequestration potential of trees when accounting for total life cycle emissions (embodied and operational), our estimations disregarded many benefits related to the use of vegetation around buildings. For example, the effect of greeneries on moderating the local microclimate and their indirect contribution to reducing heating and cooling loads, and therefore providing energy savings, were out of the scope of this paper. Regarding the LCA calculations, several premises aiming at conservative results were adopted. The potential end-of-life treatment of materials (module D, benefits beyond building life) as well as the biogenic carbon stored in wood products were not accounted for in the baseline scenario; the environmental impact related to manufacture and replacements of the PV system in the FBL was included in the LCA calculations, but the system is currently used for research purposes only, and the electricity generation as a renewable energy source was not counted yet. There is also available space to install a green roof, providing additional direct carbon sequestration.

2.5.4 Additional Scenarios and Directions for Future Work

As presented in Table 13, we used the LCA results from the FBL's baseline scenario (83,522 kgCO_2eq calculated with One Click) to demonstrate a complete set of strategies that could be considered in order to reach a net-zero carbon balance. The complete set includes the benefits from end-of-life treatment materials (module D), urban trees planted around the building, on-site PV generation, and a green roof.

As discussed, in the FBL, the module D could reduce the final GWP by 35,885 kgCO_2eq over 60 years (see Table 8). In addition to that, the carbon sequestration potential of a garden full of urban trees could offset an additional 14,145 kgCO_2eq over 60 years (see Table 11). In addition, we can roughly estimate the annual on-site electricity generation related to the PV system that is already installed on the façade and calculate the respective CO_2eq emissions displaced from the energy grid. Based on solar data from NRC (2015) the estimated photovoltaic potential (kWh/kWp) considering vertical panels under southern Quebec's climate conditions is equal to 873 kWh/kWp. The 15 m² PV system on FBL's façade has an installed capacity of 1.6320 kWp, which means that it can produce up to 1,425 kWh/year. In One Click LCA, each kWh of electricity generated in Quebec incurs 0.010234 kgCO_2eq emissions; therefore, over 60 years, the PV system would be able to offset an additional 875 kgCO_2eq. Finally, if we also include in our approach a properly fertilized and irrigated green roof of 130 m² removing 25.8 kgCO_2eq/m² per year for 10 years, as reported by Luo et al. (2015) this solution could offset an additional 33,540 kgCO_2eq.

Putting all these CO_2eq removals together, the total offset would be equal to 84,445 kgCO_2eq. Thus, the final carbon balance applied to the FBL's baseline scenario would result in (–) 893 kgCO_2eq, which means that carbon neutrality could be achieved for this scenario.

Table 13. CO_2 offset from additional strategies in FBL (kgCO_2eq over life cycle).

Benefits beyond building's life (from EOL treatment of materials)	35,885
Garden fully covered by urban trees	14,145
1.63 kWp vertical PVs system electricity generation	875
130 m² irrigated and fertilized green roof *	33,540
Total emissions offset	**84,445**
Final balance with addition solutions:	****83,522 – 84,445 = – 893**

* For the green roof, a 10y calculation period was assumed, since this kind of vegetation may have a shorter life cycle.
** See Table 8

2.6 Conclusions

This paper presents a framework and general approach, applied to real case studies, to address the feasibility of planting trees around buildings as a nature-based solution to achieve carbon neutral buildings using life cycle carbon analysis. This work shows that, for those buildings that still consume natural gas (such as the single-detached house), or for those places where the electricity grid is not yet based on renewable sources, it is not feasible to reach carbon neutrality considering just the sequestration potential of trees. However, in the case of all-electric buildings (such as the FBL), it has been shown that this solution could mitigate 16.9% to 17.1% of the building's life cycle carbon emissions without considering on-site electricity generation.

Based on the analysis of the different scenarios and assumptions presented in this paper, it seems to be possible to achieve a carbon balance closer to net-zero when expanding the strategies with approaches including other types of green solutions and on-site electricity generation.

Coupling those strategies with the indirect benefits of vegetation (i.e., energy savings), the use of nature-based materials (biogenic carbon storage), and the use of recyclable/reusable materials may be a consistent pathway towards the design and operation of carbon neutral buildings.

The analysis presented in this work has also shown that LCA studies can be very sensitive to decisions made during the calculation process. But the LCA results are still very useful for indicating the relative importance of a process in the different life cycle stages, or for estimating the expected magnitude of the impacts related to a specific material. The framework developed in this paper will be applied to investigate the contribution of urban greeneries and wood products to carbon neutral buildings and neighborhoods including both new constructions and retrofits for various building types in our future work.

3 Life Cycle Assessment of the Environmental Benefits of Using Wood Products and Planting Trees at an All-Electric University Laboratory (Manuscript #2)

3.1 Authors' Contribution

This section is also published in Buildings journal, by MDPI, and it expands the results for the case study of the Future Building Laboratory (FBL) addressed on the Manuscript #1. The current study focused on the estimation of environmental benefits associated with the use of wood products, biogenic carbon content, and end-of-life treatment of materials. Felipe Grossi (Master's student and author of this thesis) is the first author of the paper, and has contributed with the investigation, validation, and writing-original draft preparation, while Dr. Hua Ge and Dr. Radu Zmeureanu supervised the project and co-contributed with the conceptualization, methodology, data curation, resources, funding acquisition, editing and review.

3.2 Introduction

Wood products, such as plywood and mass timber, are manufactured using wood sourced from trees. During the growth process, trees absorb carbon dioxide from the atmosphere and store it as biogenic carbon in their biomass (trunks, branches, roots, and leaves) (Nowak & Crane, 2001). When these trees are harvested and transformed into wood products for construction or other long-term applications, the carbon they have sequestered remains stored in non-atmospheric pools, such as in the timber structure of a building, which is characterized as temporary carbon storage (Levasseur et al., 2012). Temporary carbon storage can help mitigate climate change because it avoids some radiative forcing by delaying the increase in greenhouse gas concentration in the atmosphere (Brandão et al., 2013) and buys time while technology evolves, and society progresses towards low-carbon energy sources (Dornburg & Marland, 2008).

From an environmental standpoint, wood products can offer a substitute for energy-intensive materials like concrete and steel (Chen et al., 2020; Pierobon et al., 2019). Furthermore, there are benefits related to the end-of-life (EOL) treatment of wood. Wood waste can be incinerated as a biofuel, reducing fossil emissions from residential heating systems or traditional grid-mix generation (Cesprini et al, 2020). If wood products are disposed of in landfills, where they are consistently covered by other materials, the biogenic carbon within the wood biomass can be permanently stored, since the decay processes are significantly reduced due to limited oxygen penetration (Ximenes et al., 2015; Wang et al., 2013; Micales & Skog, 1997). Ximenes et al. (2019) conducted experiments under laboratory conditions to simulate anaerobic biodegradation in landfills and found almost negligible rates of carbon losses in wood, less than 5%. Alternatively, wood products in good condition can be directly reused at the end of their life, while those unsuitable for reuse can be applied as raw material for, e.g., particle board and OSB (Höglmeier et al., 2013; Bresserer et al., 2021; Titunin et al., 2022), or repurposed in innovative materials, such as in low-carbon bio-concretes (to replace mineral aggregates (Araujo et al., 2022) or cement (Ercan et al., 2023)), thus contributing to the stimulation of circular economy markets.

In this context, significant efforts have been made to establish methods for quantifying the benefits of wood products and the temporary storage of carbon in biogenic materials (Brandão et al., 2013). Life cycle assessment (LCA) has emerged as a powerful tool to estimate the environmental impacts of processes and systems and to identify opportunities to reduce these impacts. The ISO 14040/14044 (2006) standards provide the basis for the application of LCA. However, as a general framework, it does not go into detail about the large variety of processes and products that LCA studies usually address (ILCD, 2010). To narrow down the range of choices left for the individual practitioner and promote consistency and transparency in LCA, additional standards and methods have been developed (EN 15978 (2011), EN 15804 (2019), ISO 21930 (2017), EN 16449 (2014), ILCD Handbook (2010), PAS-2050 (2011), Levasseur et al. (2010; 2012), Costa & Wilson (2000), and Vogtländer et al. (2014)).

However, when it comes to bio-based materials, the environmental benefits associated with biogenic carbon sequestration and storage, as well as benefits obtained at the end-of-life of materials, are often excluded from the quantification of global warming potential (GWP) or treated as optional supplementary information (ISO 21930, 2017). To address these issues, this paper presents the carbon life cycle assessment of a case study, focused on the calculation of potential benefits beyond the building's life (referred to as Module D in LCA) under three end-of-life scenarios for wood products. It also demonstrates how and when to account for biogenic carbon content in wood products according to each end-of-life scenario, and the benefits of carbon sequestration from trees. The life cycle stage defined as Module D by the EN 15978 (2011) encompasses all avoided emissions that could be achieved through the end-of-life treatment of building materials such as energy recovery, recycling, and reuse. This stage is one focus of the paper.

This case study is an expansion of the results presented by Grossi et al. (2023) for the life cycle assessment of a recently built research facility located at Concordia University, in Montreal, with a focus on nature-based solutions and their share of contribution to reducing the carbon footprint of buildings.

3.3 Literature Review

The literature review provided in this paper also expands the literature presented by Grossi et al. (2023), with a focus on LCA standards and methodologies to quantify the benefits related to nature-based solutions and the end-of-life treatment of biogenic materials.

Considering LCA standards such as EN 15978 (2011), EN 15804 (2019), ISO 21930 (2017), and the International Reference Life Cycle Data System (ILCD) Handbook (2010), as well as relevant studies addressing the cradle-to-cradle life cycle assessment of nature-based solutions for buildings, the research question that guided the literature search was:

"From an LCA perspective, how can we quantify and report the benefits of planting trees and integrating wood products in the design of buildings?"

Additional questions were derived:

- How end-of-life benefits from wood products are calculated and reported in LCA?
- How the benefits of biogenic carbon storage in wood products are estimated?
- How the benefits of carbon sequestration from trees are estimated?
- What are the LCA standards addressing the calculations related to biogenic carbon?
- Is there any standard (ISO, EN, ILCD, PAS) that provides credits for delayed emissions?

3.3.1 LCA Studies in the Literature

Wood products and trees have regained attention in recent years as sustainable solutions due to their renewable nature and potential for climate mitigation. Several studies have examined the environmental benefits of using wood products as an alternative solution for concrete, steel, and other energy-intensive materials (Wang & Dong, 2023; Liang et al., 2020; Hafner & Schäfer, 2017;

Greene et al., 2023; Guardigli et al., 2011). However, most of these studies focus on the manufacturing, use, and disposal phases (cradle-to-grave). Studies that include potential end-of-life benefits (Module D) and biogenic carbon content in their LCA analysis are scarce in the literature (Tellnes & Rønning, 2019), as they require an optional calculation step and product-level information that is often unavailable (Delem & Wastiels, 2019).

In addition to that, many LCA studies considered on-site photovoltaic electricity production as the primary strategy for balancing carbon emissions and reducing the carbon footprint of buildings (Bhavsar et al., 2020; Oreskovic et al., 2021; Evolv, 2018). However, about 80% of the worldwide commercially available PV panels are manufactured in China (IEA, 2022) a country with 88% of its energy grid-mix relying on fossil fuels (Climate Transparency, 2021). Consequently, since PV manufacturing is highly energy-intensive, it is possible that the net environmental benefits associated with photovoltaic solutions have been overestimated in some LCA studies.

Alternatively, there are other design strategies that could be integrated into the portfolio of sustainable solutions for buildings. In the case of nature-based solutions, there is only a small number of papers (Grossi et al., 2023; Luo et al., 2015; Kuittinen et al., 2016) that account for the direct carbon sequestration of trees. None of these studies includes the assessment of biogenic carbon content or the consideration of end-of-life benefits from wood products among the strategies to reduce the carbon footprint of buildings. As a result, there is a gap in the literature regarding the completeness of LCA studies, either in terms of building components/materials or in terms of life cycle stages included in the assessment.

The novelty of this paper lies in its comprehensive LCA approach, specifically applied to a real building constructed with wood-based materials. Unlike most LCA studies, this research considers all stages of the life cycle, from cradle to cradle, with a focus on estimating the potential advantages offered by nature-based design, an aspect not included in our previous LCA analyses.

3.3.2 LCA Standards

The ISO 14040/14044 (2006) standards present the general framework, requirements, and guidelines for conducting life cycle assessments of any kind. In the context of buildings and construction products, EN 15978 (2011) and ISO 21930 (2017) cover these aspects, respectively. Both standards provide information about Module D (benefits beyond a building's life), but EN

15978 (2011) treats this module as supplementary information (separated from final results, but mandatory), while ISO 21930 (2017) treats it as an optional module.

Regarding the estimation of biogenic carbon, ISO 21930 (2017), EN 15804+A2 (2019), EN 16449 (2014), ILCD Handbook (2010), and PAS 2050 (2011) provide guidance. All of these standards adopt a default −1/+1 approach, but ILCD and PAS have an additional 'optional' method using a discounting system for delayed emissions. In the default −1/+1 approach, the biogenic CO_2 uptake during forest growth (which is transferred to the building system) is reported as a negative (−1) emission in module A as separate information. At the end-of-life of the building, the release of biogenic CO_2 is reported as a positive emission (+1) in module C, or it is transferred to a subsequent product system in the case of recycling or reusing, in module D.

Although out of the scope of this paper, if the time when an emission takes place is considered, the benefits from temporarily stored biogenic carbon can be expressed as a 'credit', as described in the additional optional method from ILCD and PAS 2050. For instance, if 1 kg CO_2 absorbed from the atmosphere is stored as biogenic carbon for 60 years and then released back into the atmosphere, the carbon flow would be represented by a negative value indicating uptake (−1 $kgCO_2eq$), a positive value indicating release (+1 $kgCO_2eq$), and an additional negative value of −0.6 $kgCO_2eq$ as a reward for the 60-year delay in emission. In this case, the final carbon balance would be −0.6 $kgCO_2eq$, even though the net balance in practice is zero. This rewarding system incorporates an impact factor of −0.01 $kgCO_2eq$ per kg of CO_2 stored per year, based on the GWP100 perspective, which categorizes emissions delayed for over 100 years as long-term storage.

As explained in ISO 21930 (2017), various approaches have been proposed to address delayed emissions in the quantification of the GWP, including approaches based on discounting systems (ILCD and PAS 2050) or based on time-dependent characterization factors within a predefined reference study period (such as the dynamic LCA proposed by Levasseur et al. (2010, 2012)).

However, due to the lack of common acceptance for these approaches, such calculations are not included in the quantification of GWP. Therefore, following the precautionary principle of LCA, no extra credit (e.g., −0.6 $kgCO_2eq$) related to delayed emission (temporary carbon storage for less than 100 years) was considered in this paper.

3.4 Materials and Methods

3.4.1 Cradle-to-Cradle LCA of Future Buildings Laboratory

Using the case study of Future Buildings Laboratory (FBL), this paper estimates the impact mitigation potential associated with end-of-life treatment and biogenic carbon content in wood products, and direct carbon sequestration from trees that could potentially be planted around the research facility. The investigation was carried out using One Click LCA (2023), automated LCA software developed for the estimation of the carbon footprint of buildings and products. The software's datasets are regionally customized, taking into account factors such as electricity grids, transportation modes, and material options based on the building's location. One Click LCA employs data cards to provide the calculation steps and characterization factors used in the assessment, allowing users to understand the impact contribution of each design decision. Additionally, the software is third-party certified for compliance with ISO and EN general and construction-specific LCA standards.

The impact assessment started with the quantification of all materials and equipment specified in the design drawings, including those used in foundations, superstructure, roof, exterior walls, interior walls, finishes, windows, doors, HVAC, and BIPV system. This list of materials, organized by building assembly, was mapped within the LCA software, where each input from the design was linked to an inventory data point (e.g., a specific construction material option). Then, the next input was the annual electricity consumption, which was previously estimated based on the simulation results described by Grossi et al. (2023). The last software input was the vegetation carbon withdrawals, (i.e., the number and type of trees that could be planted around the building).

The LCA results are presented in terms of GWP, under three end-of-life scenarios for wood products: (1) wood incineration with energy recovery, (2) wood landfilling, and (3) wood reusing. The calculation period was defined as 60 years. The benefits beyond the building's life, referred to as module D in the life cycle stages, were included in the final results, as well as the biogenic carbon content of wood products (where applicable) and trees. Further information regarding the inclusion or exclusion of biogenic carbon is provided in the Results and Discussion section.

Opened in 2021, the Future Buildings Laboratory is a research facility situated at Concordia University's Loyola Campus in Montreal. Spanning an area of 125 m^2, this wood-based laboratory operates entirely on electricity and is dedicated to developing innovative concepts for carbon-neutral buildings. The facility is designed to accommodate the testing of various technologies, including building-integrated photovoltaics (BIPV), motorized shading devices, diverse building envelope systems, cutting-edge building materials, HVAC systems, urban wind energy, and more. Additionally, the laboratory has a garden area measuring 410 m^2.

As shown in Figure 14, the building is composed of a concrete slab-on-grade foundation, engineered wood structure made of glued laminated timber, insulated wood frame walls, and insulated metallic roof. The HVAC system consists of air-source heat pump, air-handling unit with heat recovery, humidifier, and electric heater. Presently, the four test cells on the southern facade feature building-integrated photovoltaic/thermal (BIPV/T) and semi-transparent PV curtain wall systems; however, these systems have only been utilized for research purposes, and have not yet been used to generate electricity for the facility's operation. Therefore, their potential to displace carbon emissions from grid-purchased electricity is not considered in this study.

The annual electricity consumption related to the HVAC system, equipment, and interior lighting was modeled in DesignBuilder (EnergyPlus) (v7.0.2.004, 2022), using the design parameters detailed in Grossi et al. (2023). The simulated electricity consumption is 8868 kWh/year, which is equivalent to 70.94 kWh/m^2 of heated floor area per year and 11.42 kWh/m^3 of heated internal volume per year.

Figure 14. Future Buildings Laboratory in different construction stages.

3.5 Results and Discussion

The LCA conducted for the case study building assessed three end-of-life scenarios for wood products: (1) wood incineration with energy recovery, (2) wood landfilling, and (3) wood reusing. The remaining material types were assigned default end-of-life treatments provided by One Click LCA, which are based on local market practices.

The results presented in Table 14 are divided into two parts. The first part displays the impacts associated with modules A to C, representing the building's embodied and operational emissions from a cradle-to-grave perspective. The second part shows the benefits that can be achieved beyond a building's life through the end-of-life treatment of materials (module D), as well as the benefits derived from biogenic carbon storage in wood products and carbon sequestration from trees. In module D, 'benefits' refers to avoided emissions such as those achieved through energy recovery from wood incineration, while the biogenic carbon 'benefit' refers to the amount of carbon contained within bio-based products and the carbon sequestered by trees. Positive GWP values correspond to the emissions, while negative values correspond to the avoided emissions.

Table 14. Whole building cradle-to-cradle LCA results for the Future Buildings Laboratory.

Modules	Result Category	Global Warming Potential ($kgCO_2eq$ over 60 years) *		
		SCENARIO 1 Wood Incineration w/Energy Recovery	**SCENARIO 2 Wood Landfilling**	**SCENARIO 3 Wood Reusing**
A1–A3	Construction Materials	55,715	55,715	55,715
A4	Transportation to site	2131	2131	2131
A5	Construction/installation processes	2614	2606	2602
B4–B5	Material replacement and refurbishment	14,291	14,291	14,291
B6	Energy consumption	5445	5445	5445
C1–C4	End-of-life process (transport, processing, disposal)	3139	2930	2809
TOTAL	**Impacts from modules A to C**	**83,338**	**83,121**	**82,995**
D	Benefits beyond building's life (wood products)	−1070	0.00	−7473
D	Benefits beyond building's life (other products)	−10,533	−10,533	−10,533
Other	Benefits biogenic carbon in wood products	0.00	−32,220	−32,318
Other	Benefits biogenic carbon in trees (CO_2 sequestration)	−19,361	−19,361	−19,361
TOTAL	**Benefits from module D + biogenic carbon**	**−30,964**	**−62,115**	**−69,686**
TOTAL	**Final balance (impacts + benefits)**	**52,373**	**21,006**	**13,309**

* Obs.: Global warming potential (GWP) is used in LCA to assess the impact of any GHG on the environment expressed by the equivalent amount of CO_2 emission.

In the first part (modules A to C), the results are nearly identical for all the scenarios, ranging from 82,995 to 83,338 $kgCO_2eq$. The differences are attributed to process-specific burdens that are adjusted when the end-of-life scenario for wood is changed (e.g., adjusts for the construction site wood waste processing). However, in the second part, when the benefits from module D and the biogenic carbon in wood products and trees are included, there is an overall reduction in the final balance results, which significantly vary across each scenario.

The final balance in scenario 1 (wood incineration) is 52,373 kgCO_2eq; in scenario 2 (wood landfilling), it is 21,006 kgCO_2eq; and in scenario 3 (wood reusing), it is 13,309 kgCO_2eq. Thus, the wood reusing scenario resulted in the lowest carbon footprint, assuming that all wood products can be repurposed in new applications, either through direct reinstallation or as raw material for secondary products. The wood landfilling scenario presented slightly higher GWP results, as there is no direct benefit from landfilling that can be assigned to wood products in terms of avoided emissions, only in terms of biogenic carbon storage. In the case of wood incineration, the benefits from energy recovery are diminished due to the case study location (Quebec), where the grid electricity is predominately sourced from renewable hydropower. If the wood waste could be sent to other provinces (where grid electricity still relies on fossils) or used to power district heating systems based on natural gas, the benefits would be significantly greater.

A detailed breakdown of benefits related to module D and biogenic carbon, as well as the share of contribution of each benefit (expressed as the percentage of carbon reduction compared to impacts from modules A to C), is presented in Table 15.

It is important to emphasize that, apart from the wood products, all other material types received the same end-of-life treatment in all scenarios, which is based on current market practices (i.e., recycling for steel, incineration with energy recovery for plastics, and landfill to inert materials (One Click LCA, 2023). Therefore, module D encompasses benefits other than those specifically related to wood products.

Table 15. Avoided impacts from benefits in module D, biogenic carbon, and carbon sequestration.

Material Type	Benefit	GWP [$kgCO_2eq$ over 60 years; (% Carbon Reduction) *] SCENARIO 1 Wood Incineration w/Energy Recovery	SCENARIO 2 Wood Landfilling	SCENARIO 3 Wood Reusing
Wood	Energy for district heating (avoided grid-mix emissions)	−1070 (1.3%)	0.00 (0.0%)	0.00 (0.0%)
	Landfill disposal (no direct benefits from EOL treatment)	0.00 (0.0%)	0.00 (0.0%)	0.00 (0.0%)
	Reuse material (avoided emissions from new manufacturing)	0.00 (0.0%)	0.00 (0.0%)	−7473 (9.0%)
Plastic	Energy for district heating (avoided grid-mix emissions)	−186 (0.2%)	−186 (0.2%)	−186 (0.2%)
Steel	Recycling (avoided emissions from new manufacturing)	−10,296 (12.4%)	−10,296 (12.4%)	−10,296 (12.4%)
Gypsum	Recycling (avoided emissions from new manufacturing)	−50 (0.1%)	−50 (0.1%)	−50 (0.1%)
Inert	Landfill disposal (no direct benefits from EOL treatment)	0.00 (0.0%)	0.00 (0.0%)	0.00 (0.0%)
	Module D, benefits from end-of-life treatment	**−11,603 (14.0%)**	**−10,533 (12.7%)**	**−18,006 (21.7%)**
Wood	Biogenic carbon in products (permanent storage)	0.00 (0.0%)	−32,220 (38.8%)	−32,318 (38.9%)
Trees	Biogenic carbon in trees (carbon sequestration and storage)	−19,361 (23.2%)	−19,361 (23.3%)	−19,361 (23.3%)
	Benefits from biogenic carbon	**−19,361 (23.2%)**	**−51,581 (62.1%)**	**−51,679 (62.2%)**
	TOTAL BENEFITS (module D + biogenic carbon)	**−30,964 (37.2%)**	**−62,115 (74.8%)**	**−69,686 (83.9%)**

Obs.: Share of contribution (i.e., % carbon reduction) in relation to LCA results for modules A to C.

3.5.1 Scenario 1: Wood Incineration With Energy Recovery

In Scenario 1, where wood products are incinerated in centers of district energy (typically for powering district heating systems), the life cycle GWP decreases from 83,338 $kgCO_2eq$ (total of A to C, Table 14) to 52,373 $kgCO_2eq$ (final balance, Table 14). As presented in Table 15, this represents an overall impact mitigation of 37.2%, with only 1.3% (−1070 $kgCO_2eq$) attributed to avoided grid emissions by using wood as a power source, 23.2% (−19,361 $kgCO_2eq$) attributed to carbon sequestration by trees, and the remaining 12.7% due to end-of-life benefits from other materials, mainly steel recycling.

Although the biogenic carbon from wood products cannot be accounted for in this scenario (because the carbon is released when the wood is burned for energy recovery), there is still the benefit of avoiding some fossil fuel emissions from Quebec's traditional grid-mix, and the unaccounted value of temporary carbon storage for 60 years.

The estimation of benefits from this end-of-life scenario was based on the information provided in Table 16 and Equation (6).

Table 16. Information used to calculate the benefits of wood incineration with energy recovery.

Components	Value	Unit	Source
Total mass of wood products	20,913	kg wood	Design specifications
Heating value of wood (approx.)	5.00	kWh/kg wood	One Click LCA, 2023
Quebec's electricity grid GHG intensity	0.010234 *	$kgCO_2eq/kWh$	StatCan 2020; Ecoinvent 3.4

* Including methane emissions from rotting vegetation in hydro reservoirs.

$$\text{Avoided Emissions} = (-)\ \text{Total mass of wood products} \times \text{Heating value of wood} \times \text{Quebec's electricity grid GHG intensity} \qquad (6)$$

where the avoided emissions from burning wood waste instead of using electricity from the Quebec electricity grid are provided in $kgCO_2eq$, the total mass of wood products in kg of wood (calculated using product-specific densities), the heating value of wood in kWh/kg of wood, and Quebec's electricity grid GHG intensity in $kgCO_2eq/kWh$. The total benefit of burning the wood waste is estimated at −1070 $kgCO_2eq$.

Since Quebec's electricity grid relies mostly on hydropower, the GHG intensity of electricity generation is low (i.e., 0.010234 $kgCO_2eq/kWh$, StatCan 2020). Therefore, the benefits (avoided grid-mix emissions) that can be offset by wood incineration are also low. However, considering the case of other provinces such as Ontario, with a grid GHG intensity of 0.0671 $kgCO_2eq/kWh$, or Alberta, with a GHG intensity of 0.37 $kgCO_2eq/kWh$ (One Click LCA (2022) based on StatCan (2021)), the benefits of end-of-life incineration could be significantly greater.

3.5.2 Scenario 2: Wood Landfilling

In Scenario 2, where wood products are landfilled, the life cycle GWP decreases from 83,121 $kgCO_2eq$ (Table 14, total of A to C) to 21,006 $kgCO_2eq$ (Table 14, final balance). The overall impact mitigation is 74.8% (Table 15), with 38.8% attributable to the biogenic carbon content permanently stored in landfilled wood waste, 23.2% attributable to carbon sequestration by trees, and the remaining portion due to end-of-life benefits from other materials. Therefore, in this scenario, the benefits from nature-based solutions are not included in module D (because there is no direct benefit related to the landfilling process), but they are accounted for separately, as permanent carbon storage in landfilled wood products (−32,220 $kgCO_2eq$) and carbon sequestration by trees (−19,361 $kgCO_2eq$).

Several studies and LCA methodologies (Ximenes et al., 2015; Wang et al., 2013; Micales & Skog, 1997; UL Environment, 2020) demonstrate that only a small proportion of wood degrades in landfills, which can take decades to occur. Most of the carbon is kept permanently stored. According to calculations in One Click LCA (based on the Ecoinvent v3.4 upstream database), the environmental impacts from landfilling biogenic materials were estimated using an overall emission factor of 0.0046 $kgCO_2eq$/kg dry wood. Since no direct benefits are derived from the landfilling process (only those related to biogenic carbon storage), the impacts from wood decay are included in modules C1–C4.

3.5.3 Scenario 3: Wood Reusing

In Scenario 3, where wood products are reused after their end-of-life, the life cycle GWP decreases from 82,995 $kgCO_2eq$ (Table 14, total of A to C) to 13,309 $kgCO_2eq$ (Table 14, final balance). The overall impact mitigation is 83.9% (Table 15), with 9.0% (−7473 $kgCO_2eq$) attributed to wood product reuse (avoided emissions from new manufacturing), 38.9% (−32,318 $kgCO_2eq$) attributed to biogenic carbon content within the wood products, 23.3% (−19,361 $kgCO_2eq$) from carbon sequestration by trees, and the remaining portion due to end-of-life benefits from other materials.

It is important to note that in this scenario, the benefits from wood products in module D were calculated considering potential emissions avoided from manufacturing the exact same product. However, in practice, part of the wood waste may be redirected as raw material for secondary applications and part may be directly reused (see Höglmeier et al. (2013) for further examples). Therefore, the end-of-life benefits (in module D) attributed to wood products were estimated using manufacture-specific impacts according to One Click LCA datasets, listed in Table 17.

Table 17. Manufacturing impacts for different wood products.

Wood Product	**Value**	**Unit**	**Reference**
Softwood plywood	0.39	$kgCO_2eq$/kg wood	Athenasmi (2018); PCR FPInnovations (2015)
Softwood lumber	0.14	$kgCO_2eq$/kg wood	UL Env. PCR Part B (2020); Athenasmi (2018)
W. red cedar bevel siding	1.07	$kgCO_2eq$/kg wood	WRCLA (2018); PCR FPInnovations (2011)
Glued Laminated Timber	0.39	$kgCO_2eq$/kg wood	Athenasmi (2018); PCR FPInnovations (2015)
I-joist manufacturing	0.33	$kgCO_2eq$/kg wood	Athenasmi, (2013); PCR FPInnovations (2011)

3.5.4 Biogenic Carbon in Wood Products (Carbon Storage)

In the case of wood products, the biogenic carbon content presented in sections 3.5.1 – 3.5.3 is incorporated into One Click LCA calculations in two ways: (1) the value is provided in the building material EPD using a functional unit (e.g., $kgCO_2eq/kg$ of product), which represents the best-case scenario; and (2) the value is not declared in the EPD, and One Click LCA provides a close estimation based on industry averages.

In both situations, the guidelines of ISO 21930 (2017) and EN 16449 (2014) are followed. The conversion from the biogenic carbon content of wood products to carbon dioxide is presented in Equation (7),

$$P_{CO2} = \frac{44}{12} \times c_f \times \frac{\rho_\omega \times V_\omega}{1 + \frac{\omega}{100}} \tag{7}$$

where P_{CO2} is the biogenic carbon content in terms of carbon dioxide, 44/12 is the molecular weight ratio between carbon dioxide and carbon, C_f is the carbon fraction of wood biomass (0.5 as the default value), ω is the moisture content of the product (e.g., 12%), ρ_ω is the density of product's wood biomass (in kg/m^3), and V_ω is the volume of the solid wood product (m^3).

When biogenic carbon is not declared in the EPD, there are a few assumptions used for this calculation (i.e., carbon content is assumed to be 50%, and material is assumed to be fully dry).

3.5.5 Biogenic Carbon in Trees (Carbon Sequestration)

In all scenarios, the benefit of biogenic carbon from trees was integrally accounted for in the final balances. The selected tree species have a life span that can reach two or three times the life span of the building, allowing the carbon absorbed through photosynthesis to be considered permanently stored in the biomass of trees. Additionally, when trees reach the end of their life, they can be replaced with new trees, thus reestablishing carbon sequestration. In terms of radiative forcing impacts, emissions related to the decay of a tree occurring 200 years from now may not have the same significance as current emissions.

Based on the available garden area of 410 m^2, we estimated that it is possible to plant 13 units of typical eastern Canadian trees without affecting the building-integrated photovoltaic system or pedestrian pathways. The species and number of trees included in the design (i.e., 1 eastern white pine, 10 white spruce, and 2 Balsam fir), were defined based on their average crown size, carbon sequestration rates, and tolerance to urban conditions. According to Tree Canada (2023), these trees generally grow to a height of 20–30 m, with a crown spread of 6–10 m, and have a lifespan of over 100 years.

Carbon sequestration rates were obtained from One Click LCA data points, which utilize background information from the Environmental Information Administration (1998) to estimate carbon withdrawals by vegetation in urban and suburban areas. As shown in Table 18, we estimated that the set of trees planted around the laboratory could remove 19,361 kgCO_2eq from the atmosphere over a 60-year calculation period (also refer to Table 14 and Table 15).

Table 18. Carbon sequestration results and complementary information about trees in this paper.

Tree Specie	Carbon Sequestration (kgCO_2eq/Unit*Year)	Tree Height (m)	Crown Width (m)	Life Span (Years)	No. Trees Planted (Units)	Sequestration Over 60 Years (kgCO_2eq)
Eastern white pine	47.82	30	10–12	200+	**1**	**−2869**
White spruce	25.33	25	4–6	200+	**10**	**−15,200**
Balsam fir	10.77	25	5–7	80+	**2**	**−1292**
TOTALS					**13**	**−19,361**

This result, calculated using One Click LCA, is compared with Grossi et al. (2023) for the same case study (but calculated using the tree cover area methodology proposed by Nowak et al. (2008; 2013) and Pasher et al. (2014), when the specific tree species were not defined). As shown in Table 19, Grossi et al. (2023) estimated a total carbon sequestration of 14,145 kgCO_2eq (0.575 kgCO_2eq/m^2 of tree cover area per year), while in this paper, using One Click LCA, the total sequestration is estimated to be 19,361 kgCO_2eq (0.787 kgCO_2eq per m^2 of tree cover area per year). This difference is likely due to the fact that Grossi et al. (2023) used a standardized approach based on countrywide samples of trees from the US and Canada, whereas the calculation performed in this paper is based on only three local tree species, which increases the sensitivity of the results.

Table 19. Comparison of carbon sequestration results between Grossi et al. (2023) and this paper.

	Total Carbon Sequestration (kgCO_2eq Over 60 years)	Annual Carbon Sequestration per Area (kgCO_2eq/m^2 Tree Cover)	Calculation Methods/ References
Results from Grossi et al. (2023)	14,145	0.575	Nowak et al. (2008; 2013) Pasher et al. (2014)
Results from this paper	19,361	0.787	One Click LCA (2023) EIA (1998), TreeCanada (2023)

3.5.6 Assumptions, Uncertainties, and Limitations

Some assumptions and uncertainties in this method have led to limitations and drawbacks, which are described below:

- As per ISO 21930 (2017) for wood products entering the building system, the benefits from considering the biogenic carbon may only be accounted when the wood originates from sustainably managed forests (e.g., certified by Forest Stewardship Council (FSC), Sustainable Forestry Initiative (SFI), Canadian Standards Association (CSA)).
- The extent of wood degradation in landfills (i.e., GHG emissions from wood decay) may vary depending on the landfill design and location.
- In the wood reusing scenario, the benefits from wood products in module D were calculated based on potential emissions avoided from manufacturing the exact same product. However, in practice, part of the wood waste may be redirected as raw material for secondary applications and partly directly reused.
- Only three species of trees have been considered in the current study. If other species (having different carbon sequestration rates) had been included, the impact mitigation results could have been different.
- Since the lab is not yet in operation at full capacity, the annual electricity consumption considered in the LCA was based on the energy simulation results with EnergyPlus, as described in Grossi et al. (2023).
- The indirect benefits of trees such as energy savings, wildlife conservation, and air quality, as well as the impacts related to land-use change in FBL's garden were not addressed in this paper's scope.

3.6 Conclusions

This paper presents an LCA framework that architects, designers, and engineers may consider when conducting environmental impact assessments for buildings. This work highlights the practical significance and potential benefits of nature-based design solutions, especially applied to a real building constructed with engineered wood materials, accounting for all building components and mechanical systems as they were designed. As presented in to Table 14 and Table

15, the benefits from wood products can be related to end-of-life treatment (e.g., avoided grid-mix emissions by using wood as biofuel, or by recycling other types of materials) and/or biogenic carbon storage in a product's biomass. The benefits from trees are related to carbon sequestration. In terms of impact mitigation, wood products contributed 1.3% in scenario 1, 38.8% in scenario 2, and 9% (end-of-life benefit) plus 38.9% (biogenic carbon content) in scenario 3. For all scenarios, the benefits from carbon sequestration by trees contributed 23.3%, and the benefits from the end-of-life treatment of other types of products contributed 12.7% (mainly steel recycling). From a cradle-to-cradle life cycle perspective, integrating nature-based solutions such as wood products and trees into the design of buildings and their surroundings always yields environmental benefits, but depending on the building location, one end-of-life scenario might be more favorable than the other. A combination of scenarios may be a practical approach for future studies. For the case presented in this paper, the best approach consists of reusing all wood products in good condition and repurposing the rest as secondary products. Appling them as biofuel in regions outside of Quebec, or sending them to landfills, can be an alternative. Future work could involve tracking wood waste products in the Canadian context and identifying circular economy markets for bio-based products.

4 LCA Applied to Building Retrofit

4.1 Introduction

The approach described in this chapter aims to demonstrate the process of assessing the environmental performance of a building retrofit solution using energy simulation and life cycle assessment (LCA). Energy simulation is employed to estimate the annual energy consumption achievable when introducing different improvements to envelope components, such as adding insulation, replacing windows, and providing shading. LCA, on the other hand, allows us to estimate the embodied emissions associated with the manufacture of each new envelope or HVAC component, as well as the savings in operational emissions resulting from the energy efficiency improvements. This chapter presents the case study of a 2-storey school building and addresses the application of LCA in the context of building energy retrofit under different locations scenarios.

4.2 Methodology

4.2.1 Overview

The process began with the analysis of the existing school building, located in Montreal, serving as the baseline scenario. To represent the pre-retrofit energy consumption situation, an energy model was created using DesignBuilder (EnergyPlus) (v7.0.2.006, 2022). Then, different improvements were made to the building envelope and HVAC systems, as presented in Figure 15. The improvements were incorporated one-by-one, and an individual energy simulation was run for each step. This approach allows us to visualize the relative influence of each building component enhancement on the energy consumption and carbon emission outcomes.

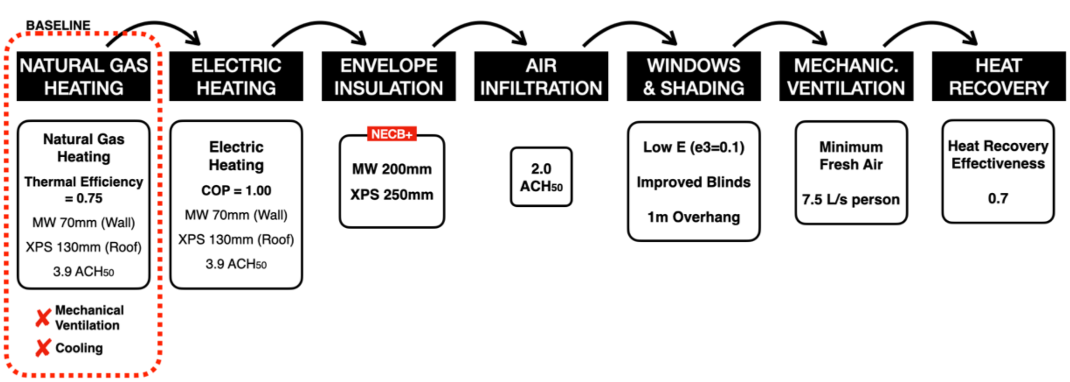


Figure 15. Overview of the retrofit design improvements (simulated at each step).

The first improvement involved replacing the natural gas heating system with an electric system, while maintaining all other components such as insulation and windows in their original state. The next step focused on increasing the thickness of the roof and exterior wall insulation to meet the U-value requirements from NECB (2020). Then, a new air infiltration value was set to represent a more airtight envelope. The subsequent enhancements included new windows, blinds, and overhangs, and finally, the mechanical ventilation and heat recovery systems.

The case study building is located in Montreal (Quebec). To demonstrate the influence of local energy grid profile on building's environmental performance, two additional sets of simulations were conducted for the same retrofit approach, but using the weather file and grid profile of Ottawa (Ontario) and Halifax (Nova Scotia). The LCA was conducted using One Click LCA (2023) software, under a 20-year calculation period perspective. Although some of the materials and equipment incorporated in the retrofit can potentially reach longer service life, the time horizon was set as 20 years aiming to avoid uncertainties from future energy scenarios and technological development, as well as secondary emissions from new replacements of building parts.

4.2.2 Case Study: School Building

The 2-story school building has a total area of 2,300 m^2. As shown in Figure 16, the exterior walls are composed of brick veneer on the outside, followed by 25 mm air gap, 70 mm of mineral wool (MW) insulation, Concrete Masonry Units, and gypsum plaster on the inner layer. The roof consists of an outer layer of rubberized asphalt, then fiberboard, 130 mm of XPS insulation, and 100 mm concrete slab. The windows are double (clear) glazing with a 13 mm air gap. The original design did not have mechanical ventilation and a cooling system.

Figure 16. Pre-retrofit design, exterior walls, and roof layers.

As presented in Tables Table 20, Table 21 and Table 22, the retrofit solution encompassed a series of enhancements. Initially, the existing natural gas heating system was replaced with an electric heating system. Subsequently, the 70-mm mineral wool insulation on the exterior walls was upgraded to a thicker 200-mm layer, and the previous 130-mm XPS insulation on the roof was replaced by a new 250-mm layer. This new envelope configuration meets the U-value requirements specified in NECB (2020). To represent a more airtight envelope, adjustments were made to the air infiltration rates in the energy simulations. The original rate of 3.9 air changes per hour (ACH) was modified to a reduced value of 2.0 ACH, both measured at 50 Pa pressure differential. Further improvements involved the replacement of the existing double (clear) glazing air-filled windows with new double-glaze low-emissivity (low E) coated windows. In addition, the conventional blinds were replaced with low-reflectance, high-transmittance shade rolls. Then, 1m-overhangs were installed to avoid overheating during summer season. Concluding the enhancements, a mechanical ventilation system was integrated into the new design, complemented by a heat recovery system.

Table 20. Comparison between baseline and retrofit design (main characteristics).

	Building Components	**Baseline Design**	**Full Retrofit Design**
HVAC	Heating System	Natural Gas	Electricity
	Cooling System	No	No
	Mech. Ventilation	No	Yes
	Heat Recovery	No	Yes (eff.= 0.7)
ENVELOPE	Wall insulation thick. (mm)	70, Mineral Wool	200, Mineral Wool
	Roof Insulation thick. (mm)	130, XPS	250, XPS
	Air Infiltration (ACH at 50 Pa)	3.9	2.0
WINDOWS	Window to Wall Ratio (%)	60	60
	Glazing type	Double (Clear)/Air	Double (Low E)/Air
	SHGC	0.76	0.60
	Shade Roll ('blinds')	Medium Opaque	L. Reflect /H. Transmit
	Overhang	No	Yes, 1m Overhang

Table 21. U-values (W/m².K) considered on the School Building retrofit.

Building Components	**Baseline Design**	**Fill Retrofit Design**	**NECB (2020)***
Slab-on-grade foundations	0.13	0.13	0.75
Exterior walls	0.42	0.17	0.24
Roof	0.22	0.12	0.14
Windows	2.71	1.38	1.73
Doors	1.40	1.40	1.90

*Obs.: Considering prescriptive thermal requirements for climate Zone 6.

Table 22. Energy simulation inputs for the School Building.

Inputs	Value	Unit
Occupancy	20.0	Person/zone
Heating setpoint	21.0	°C
Heating setback	18.0	°C
Cooling setpoint	23.0	°C
Ventilation rate (per person)	7.5	L/sec/person
Lighting power density	8.0	W/m^2
Appliances and plug loads	3.0	W/m^2
Thermal Efficiency (natural gas heating)	0.75	-
Coefficient of Performance (COP, electric heating)*	1.00	-

*Obs.: A supplementary scenario considering heat pumps (COP=2) is presented in the Appendix

4.2.3 Electricity Grid Profiles

This section focuses on presenting the electricity grid profiles of Quebec, Ontario, and Nova Scotia, as well as relevant information regarding the different types of fuel employed on electricity generation plants and space heating systems.

The local electricity profile plays a determinant role in life cycle assessment, being potentially one of the most influent factors affecting the environmental performance of a building. In this case study, we aimed on presenting different scenarios where the local grid-mix leads to contrasting conclusions regarding the benefits of building/energy retrofit, based on a carbon perspective.

Figure 17 shows the share of electricity generation by fuel type, based on information from Canada Energy Regulator (CER, 2020), for the three location scenarios assessed in this study.

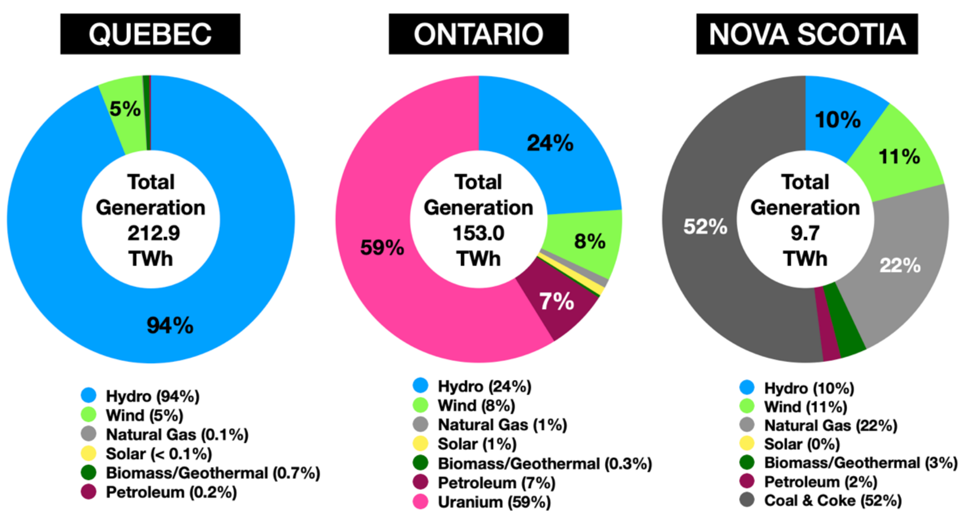


Figure 17. Provincial and territorial electricity generation by fuel type.
Source: Canada Energy Regulator, CER (2020).

4.2.3.1 Quebec Electricity Profile

Nowadays, Quebec's electricity generation predominantly relies on renewable sources, with hydropower accounting for 94% of the total and wind power contributing 5%. However, the electrification of the transportation sector could potentially lead to increased electricity demand in the coming decades. This increased demand may exert pressure to reintroduce non-renewable sources to meet the growing electricity needs. Despite this potential challenge, Quebec currently stands as one of the Canadian provinces with the least energy related GHG impacts. As reported by CER (2020), the GHG intensity of Quebec's electricity grid was 0.0015 kgCO_2eq/kWh of electricity generated in 2020. It's important to note, however, that this value does not include other impacts such as biogenic decay in hydro reservoirs (rotting vegetation emitting CO_2 and Methane (CH_4)) and emissions related to transmission processes.

In this study we considered the value of 0.01023 kgCO_2eq/kWh, sourced from One Click LCA (2023) and Athena's Transparency Document (2019). This value was calculated based on data from the Ecoinvent 3.4 (2017) databases and incorporates all carbon emissions up to the final point of consumption.

4.2.3.2 Ontario Electricity Profile

Ontario is also a province that has its electricity generation based on clean sources. The main source for electricity generation is nuclear (Uranium) (59%), followed by hydro (22%), wind (8%) and natural gas (7%) power. As reported by CER (2020), the GHG intensity of Ontario's electricity grid was 0.025 kgCO_2eq/kWh generated in 2020.

Similar to the case of Quebec, this value only reflects the emissions at the power plants. Therefore, in this study we considered the value of 0.028 kgCO_2eq/kWh of electricity used at the final point of consumption. This value was also calculated based on Ecoinvent databases, sourced from One Click LCA (2023) and Athena's Transparency Document (2019).

4.2.3.3 Nova Scotia Electricity Profile

Nova Scotia has a totally different electricity profile, which is mostly reliant on fossil fuels. The electricity generation is primarily based on coal & coke (52%) and natural gas (22%), followed by wind (11%), and hydro (10%). This scenario incurs to Nova Scotia one of the highest levels of grid-related GHG emissions in Canada. As reported by CER (2020), the GHG intensity of Nova Scotia's electricity grid was 0.670 $kgCO_2eq/kWh$ generated in 2020.

As we did for the other locations, we considered a slightly higher value of 0.680 $kgCO_2eq/kWh$, incorporating all carbon emissions up to the final point of consumption (based on One Click LCA (2023) and Ecoinvent database). Due to the different grid-mixes, the use of electricity in Nova Scotia faces 65 times more impacts than in Quebec (0.680 versus 0.0102 $kgCO_2/kWh$), and 24 times more impacts than in Ontario (0.680 versus 0.028 $kgCO_2/kWh$).

4.2.3.4 Natural Gas and Coal

Although the use of natural gas is significantly GHG intense, it can be considered an option for places reliant on coal, like Nova Scotia. The amount of CO_2 emitted in the production of 1 kWh of electricity using coal versus natural gas can vary based on several factors, including the efficiency of the power plants, the type of coal or natural gas being used, and the technology in place. On average, based on EIA (2021) coal-fired power plants emit around 1.025 $kgCO_2eq/kWh$ of electricity generated, while natural gas-fired power plants are generally more efficient, ranging from 0.180 $kgCO_2eq/kWh$ (NIR, 2021) to 0.440 $kgCO_2eq/kWh$ (EIA, 2021). The factor of 10.55 kWh/m^3 (NRC, 2015) was employed to convert the energy provided by 1 m^3 of natural gas to an energy equivalent value of electricity. In this study we considered GHG intensity of natural gas use equal to 0.218 $kgCO_2eq/kWh$ (equivalent to 2.30 $kgCO_2/m^3$), based on One Click LCA (2023) database.

4.2.4 *Embodied Emissions*

Each improvement introduced in the design (such as new insulation or new HVAC equipment) carries an environmental impact linked to manufacturing processes. This section details the materials and equipment considered in the estimation of embodied emissions tied to each design enhancement. A portion of the inputs relies on manufacturer-specific data from Environmental Product Declarations (EPDs), sourced from the One Click LCA database. For the materials or equipment where manufacturer-specific information are not available, Canadian industry averages (provided by One Click LCA) were employed. A calculation period of 20 years was considered for the assessment, but an additional scenario considering 60 years is provided in the Appendix. As required by ISO 21930 (2017), the environmental profiles reported by EPDs and employed by the LCA software are based on the accumulated radiative forcing under the GWP_{100} perspective.

4.2.4.1 Insulation & Air barrier

Data source:	EPD, Rockwool North America
Material specification:	Mineral wool insulation panels, L = 0.038 W/m.K, density 40 kg/m3, 0,038m =1 $W/m^2.K$
Environmental profile:	1.31 $kgCO_2eq$ / m^2
Project Embodied Emissions:	8,359 $kgCO_2eq$

Figure 18. Environmental profile of mineral wool insulation, (Rockwool North America, 2019)

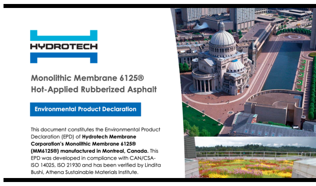
Data source:	EPD, DuPont Styrofoam Brand XPS
Material specification:	XPS insulation panels, L = 0.035W/m.K, per 100 mm, 3.8 kg/m^2, 38 kg/m^3
Environmental profile:	14.5 $kgCO_2eq/m^2$
Project Embodied Emissions:	26,621 $kgCO_2eq$

Figure 19. Environmental profile of XPS insulation, (DuPont, 2021).

Data source:	EPD, DuPont Tyvek
Material specification:	Air and water barrier system, fluid applied, 0.9 kg/m^2, Tyvek
Environmental profile:	3.5 $kgCO_2eq$ / m^2
Project Embodied Emissions:	1,621 $kgCO_2eq$

Figure 20. Environmental profile of Air barrier (DuPont, 2017).

4.2.4.2 Roofing Asphalt



Data source:	EPD, Hydrotech Membrane Corp
Material specification:	Hot-applied rubberized asphalt membrane, waterproofeng, 5.56 mm, 6.39 kg/m^2, monolithic
Environmental profile:	2.7 kgCO_2eq /m^2
Project Embodied Emissions:	3,988 kgCO_2eq

Figure 21. Environmental Profile Air Handling Unit, (Hydrotech Membrane Corp, 2018)

4.2.4.3 Windows & Shading

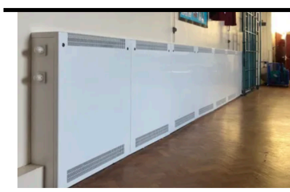
Data source:	EDP, AluQuebec
Material specification:	Aluminum frame windows, per m^2, 37kg/m^2, 30% aluminum, 61% glazing, 9% others
Environmental profile:	136.0 kgCO_2eq/m^2
Project Embodied Emissions:	67,148 kgCO_2eq

Figure 22. Environmental profile of Windows, (AluQuebec, 2019)

Data source:	EDP, Industrial Louvers, Inc.
Material specification:	Painted aluminum sunshades, 36.81 kg/m^2
Environmental profile:	229.0 kgCO_2eq / m^2
Project Embodied Emissions:	12,623 kgCO_2eq

Figure 23. Environmental profile of Overhangs, (Industrial Louvers Inc, 2021)

4.2.4.4 Electric Heating System and Air Handling Unit



Data source:	Industry average (One Click LCA, 2023)
Material specification:	Electric heating for educational and commercial buildings (per m^2)
Environmental profile:	15,05 kgCO_2eq / m^2 of building GFA
Project Embodied Emissions:	34,619 kgCO_2eq

Figure 24. Environmental profile of Electric Heating, (One Click LCA, 2023 – Industry Average)

Data source:	Industry average (One Click LCA, 2023)
Material specification:	Air handling unit, with heat recovery rotatory heat exchanger, 950 kg/unit, 10,000 m^3/h
Environmental profile:	6884.02 kgCO_2eq / unit
Project Embodied Emissions:	6,884 kgCO_2eq

Figure 25. Environmental profile of Air Handling Unit, (One Click LCA – Industry Average)

4.3 Results and Discussion

This section presents the results obtained from the school building retrofit assessment across the different stages of the retrofit process. Additionally, in order to show the influence of local weather and energy grid profile on final outcomes, the analysis also incorporated three distinct location scenarios (i.e., Montreal (Quebec), Ottawa (Ontario), and Halifax (Nova Scotia)).

For each design improvement – at each location – individual energy simulations and carbon emission estimations were conducted. The results provided in this section include annual energy consumption (in kWh/year), and total carbon emissions (in kgCO2eq over 20-year life cycle).

The assessment started with the Montreal scenario, building's original location, and then, on the other cities. A comparative analysis between cities was provided at the end of this section.

4.3.1 Results for Montreal (Quebec)

Table 23. Total annual energy use and total life cycle emissions calculated at each retrofit step, Montreal location.

	Natural Gas Heating →	**Electric Heating →**	**Envelope Insulation →**	**Air Infiltration →**	**Windows & Shading →**	**Mech. Vent. →**	**Heat Recovery**
Total Annual Energy Use [kWh/year]	**188,555**	**151,201**(-37,354)	**125,535** (-25,666)	**104,930** (-20,605)	**55,875** (-49,055)	**104,448** (+48,573)	**75,351**(-29,097)
Space Heating	149,416	112,062	87,093	66,489	33,807	33,807	33,807
Interior Lighting	27,216	27,216	26,736	26,736	10,362	10,362	10,362
Computers/Plugs	11,923	11,923	11,706	11,706	11,706	11,706	11,706
Mech. Ventilation	0.0	0.0	0.0	0.0	0.0	48,573	19,476
Total Emissions [$kgCO_2e$ over 20y]	**659,493**	**65,567**(-593,926)	**100,902** (+35,335)	**96,685** (- 4,217)	**166,416** (+69,731)	**183,348** (+16,932)	**177,393** (-5,955)
Operational Emissions	659,493	30,948	25,694	21,477	11,436	21,378	15,423
Embodied Emissions	0.0	34,619	75,208	75,208	154,979	161,970	161,970

Obs.: The values displayed between parenthesis, for instance (-37,354), represent the relative variation of results at each calculation step

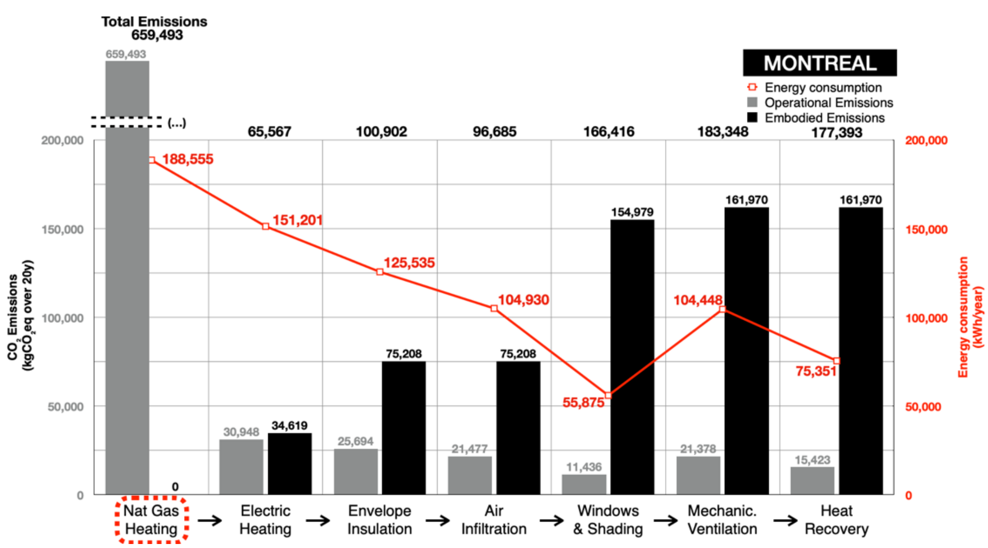


Figure 26. Energy use and carbon emissions (embodied and operational) calculated at each retrofit step, considering Montreal location.

4.3.1.1 Step 1: Existent situation (Natural Gas Heating)

The initial step in Table 23 and Figure 26, labeled as "Natural Gas Heating," represents the baseline design, reflecting the existing school building before any retrofitting takes place. In this situation, the overall annual energy consumption is 188,555 kWh/year, and the total carbon emissions are 659,493 kgCO2eq. It can be seen in Figure 26 that this substantial value of carbon emissions is entirely attributed to operational energy use emissions, with 99% associated with natural gas use for space heating, and only 1% due to lighting, computers and plugs. Embodied emissions remain at zero in this first step, as no new materials or equipment are introduced in the design during this stage.

4.3.1.2 Step 2: Natural Gas heating → Electric heating

In the second step, labeled as "Electric Heating" in Table 23 and Figure 26, the original natural gas heating system (thermal efficiency = 0.75) was replaced with an electric system (COP = 1), while all other building components (e.g., insulation, windows, etc.) remained unchanged. This modification of equipment/power source caused a decrease in the overall energy consumption, which dropped from 188,555 kWh/year to 151,201 kWh/year, since the electric heating system has a coefficient of performance of 1 (provides 1 kW of heat per kW supplied to the equipment).

Relevant changes also occurred in the total emissions, which decreased from 659,493 to 65,567 kgCO2eq over 20 years. This significant reduction in emissions is primarily attributed to the decline in operational emissions (from 659,493 to 30,948 kgCO2eq), since the new electric heating eliminated the use of natural gas and Quebec's grid-purchased electricity is predominantly sourced from hydropower, a low-carbon renewable source.

The remaining emissions (34,619 kgCO2eq) are associated with the embodied carbon tied to the manufacturing of the new heating equipment (see Figure 24 in section 4.2.4.4).

4.3.1.3 Step 3: Electric heating → Envelope insulation

The third step, labeled as "Envelope Insulation", involved replacing the exterior wall and roof insulation. The previous 70mm-layer of mineral wool on the exterior walls was upgraded to a new 200mm-layer, and the 130mm-layer of extruded polystyrene (XPS) insulation on the roof was replaced with a new 250mm-layer. New roofing asphalt and air barriers were also added where necessary.

As presented in Table 23 and Figure 26, this improvement resulted in a reduction in total energy consumption, decreasing from 151,201 to 125,535 kWh/year. The reduction is primarily due to a decrease in space heating demand, which dropped from 112,062 to 87,093 kWh/year. Minor variations in interior lighting and computer/plug demand occurred because the EnergyPlus software automatically adjusted building's internal areas when the wall thickness was changed.

Despite the savings in energy use, the total emissions still presented significant increase. Operational emissions dropped from 30,948 to only 25,694 kgCO2eq, while embodied emissions increased from 34,916 to 75,208 kgCO2eq. This indicates that the embodied emissions associated with manufacturing the new insulation materials, air barriers, and roofing membranes (i.e., 26,621 kgCO_2eq from XPS, 8,359 kgCO_2eq from mineral wool, 1,621 kgCO_2eq from air barrier, and 3,988 kgCO_2eq from the roofing membrane (see Figure 18 – Figure 20)) outweighed the reductions in operational emissions (5,254 kgCO_2eq).

4.3.1.4 Step 4: Envelope Insulation → Air Infiltration

The subsequent stage, labeled as "Air Infiltration," involved adjusting the model's air infiltration rates to reflect a more airtight envelope achieved through renovation. The initial air infiltration rate of 3.9 ACH_{50} (air changes per hour, measured at a pressure differential of 50 Pa) was reduced to 2.0 ACH_{50}. Although this value is not as low as the 0.6 ACH_{50} recommended in Passive House certifications, we aimed on a more conservative retrofit scenario. The air infiltration requirements outlined, for example, in Quebec's energy transition program Novoclimat (2021) recommends a maximum value of 1.5 ACH_{50} for new buildings, while the Ontario Building Code (2017) suggests 2.5 ACH_{50} for homes. Similarly, standards like Energy Star (2015) specify maximum air infiltration rates between 2.5 and 3.0 ACH_{50}. In light of these considerations and variations in workmanship, we selected the value of 2.0 ACH_{50} to represent the improved airtightness in our retrofitted models.

The improvement in the building's airtightness resulted in a reduction of annual energy consumption, which decreased from 125,535 to 104,930 kWh/year. The total carbon emissions also decreased from 100,902 to 96,685 kgCO_2eq due to the savings in operational energy use emissions. Embodied emissions remained unchanged from the previous stage, as no new materials or equipment were added to the design.

4.3.1.5 Step 5: Air Infiltration → Windows & Shading

The following step, labeled "Windows & Shading," encompassed the replacement of 480 m^2 of windows, along with enhancements in local shading. The previous double (clear) glazing was upgraded to double low-E coated glazing, with a lower solar heat gain coefficient (SHGC) and lower U-values (see Table 20). The improvements in local shading were achieved through the substitution of conventional blinds with low-reflectance, high-transmittance shade rolls, which helped reducing lighting use and heating loads. The installation of 1m overhangs above windows' heads was implemented with focus on avoiding overheating during summer season, since the school building doesn't have cooling system.

As presented in Table 23 and Figure 26, this comprehensive set of improvements led to a substantial decrease in overall energy consumption, decreasing from 104,930 to 55,875 kWh/year. This reduction can be attributed to both a 50% drop in energy use for space heating (from 66,489 to 33,807 kWh/year) and a reduction in interior lighting usage (from 26,736 to 10,362 kWh/year).

However, the total emissions still increased (from 96,685 to 166,416 kgCO_2eq). This is primarily attributed to the embodied emissions associated with the production of new aluminum windows (i.e., 67,148 kgCO_2eq, see Figure 22) and overhangs (12,623 kgCO_2eq, see Figure 23). On the other hand, the operational emissions reductions provided by this set of improvements could only offset 10,141 kgCO_2eq (from 21,477 to 11,436 kgCO_2eq).

4.3.1.6 Windows & Shading → Mechanical Ventilation → Heat Recovery

To meet NECB 2020 requirements, a mechanical ventilation system was integrated into the retrofit design, replacing the previous reliance solely on natural ventilation in the old building. The mechanical ventilation system was designed to operate based on a minimum fresh air supply of 7.5 L/sec/person as outlined in Table 22 and it's set to stop working when the outdoor temperature is higher than indoor. Additionally, a heat recovery system was set (coefficient of effectiveness = 0.70), contributing to a reduction in overall energy consumption. The introduction of the mechanical ventilation system initially led to a relevant increase in total energy usage (rising from 55,875 to 104,448 kWh/year). However, with the activation of the heat recovery, this consumption decreased substantially (from 104,448 to 75,310 kWh/year). The total emissions increased from 166,416 to 183,348 kgCO_2eq (without the heat recovery) and turned to decrease with the activation of the heat recovery (from 183,348 to 177,393 kgCO_2eq).

4.3.1.7 Outcomes (Montreal)

Table 24. Comparison of results for Montreal, baseline versus full retrofit.

	Baseline (a) (NAT GAS HEATING)	Baseline (b) (ELECTR. HEATING)	Full Retrofit (c) (ELECTR. HEATING)	VARIATION	
				(a) to (c)	(b) to (c)
Total Annual Energy Use (kWh/year)	**188,555**	**151,201**	**75,351**	**-113,204** (-60%)	**-75,850** (-50%)
Space Heating	149,416	112,062	33,807		
Interior Lighting	27,216	27,216	10,362		
Computers/Plugs	11,923	11,923	11,706		
Mech. Ventilation w/ heat recovery	0.0	0.0	19,476		
Total Emissions (kgCO_2eq over 20y)	**659,493**	**65,567**	**177,393**	**-482,100** (-73%)	**+111,826** (+170%)
Operational Emissions	659,493	30,948	15,423		
Embodied Emissions	0.0	34,619	161,970		

As shown in Table 24, the 'baseline (a)' represents the existing school building, which uses natural gas for space heating. The 'baseline (b)' shares the same characteristics, with the exception of the gas heating system being replaced by an electric one. These two scenarios were compared with the final design, labeled as 'full retrofit (c)', which incorporates all the design improvements previously mentioned in this chapter.

From the baseline (a) to the full retrofit (c), there is a reduction of 113,204 kWh/year in total energy use, primarily in the energy use for space heating, attributed to the enhancements made to the building envelope and COP of electric heating. Meanwhile, total emissions decrease 482,100 kgCO_2eq, notably due to the savings in operational emissions, attributed to the replacement of natural gas with electric heating. Quebec's electricity grid is based on hydropower, which is a low-carbon source (i.e., 0.01023 kgCO_2eq/kWh), while the use on natural gas for heating incurs significant impacts (i.e., 0.218 kgCO_2eq/kWh). As a result, the transition from (a) to (c) yields savings in operational emissions that outweighing any potential increases in embodied emissions associated with the production of materials and equipment.

However, when examining the transition from (b) to (c), where the pre-retrofit design already includes electric heating, the conclusions undergo significant differences. There is a reduction of 75,850 kWh/year in total energy use associated with building envelope enhancements. However, in terms of total emissions, an increase of 111,826 kgCO_2eq is observed. This is attributed to the fact that baseline (b) already uses electric heating and, given Quebec's current low grid-electricity GHG intensity, the savings in operational emissions are unable to offset the embodied emissions from new materials and equipment introduced. In this context, the decision to undertake a retrofit may not appear justified solely from a carbon perspective. Nevertheless, its viability remains valid considering the potential reduction in electricity demand derived from energy efficiency, as well as the financial savings and enhanced user comfort.

4.3.2 Results for Ottawa (Ontario)

The same procedure was carried out using identical baseline design and retrofit solutions but considering the weather file (and electricity grid profile) from Ottawa (Ontario).

The results calculated at each step of the retrofit are presented in Table 25 and Figure 27. To avoid overlapping information about the intermediate steps (previously discussed for the Montreal scenario), we concentrated the analysis on the final outcomes, comparing the baseline designs (a) and (b) with the full retrofit (c), as presented in Table 26.

Table 25. Total energy use and total emissions calculated at each retrofit stage, considering Ottawa location.

	Natural Gas Heating →	**Electric Heating →**	**Envelope Insulation→**	**Air Infiltration →**	**Windows & Shading →**	**Mech. Vent. →**	**Heat Recovery**
Total Annual Energy Use [kWh/year]	**228,055**	**180,834** (-47,221)	**150,145**(-30,689)	**124,193**(-25,952)	**66,021**(-58,172)	**125,862**(+59,841)	**90,162** (-35,700)
Space Heating	188,884	141,663	111,673	85,721	45,282	45,282	45,282
Interior Lighting	27,248	27,248	26,766	26,766	9,033	9,033	9,033
Computers/Plugs	11,923	11,923	11,706	11,706	11,706	11,706	11,706
Mech. Ventilation	0	0	0	0	0	59,842	24,141
Total Emissions [kgCO₂e over 20y]	**845,506**	**135,886** (-709,620)	**159,289**(+23,403)	**144,756**(-14,553)	**191,951**(+47,195)	**232,453**(+40,502)	**212,461**(-19,992)
Operational Emissions	845,506	101,267	84,081	69,548	36,972	70,483	50,491
Embodied Emissions	0	34,619	75,208	75,208	154,979	161,970	161,970

Obs.: The values displayed between parenthesis, for instance (–47,221) represent the relative variation of results at each calculation step.

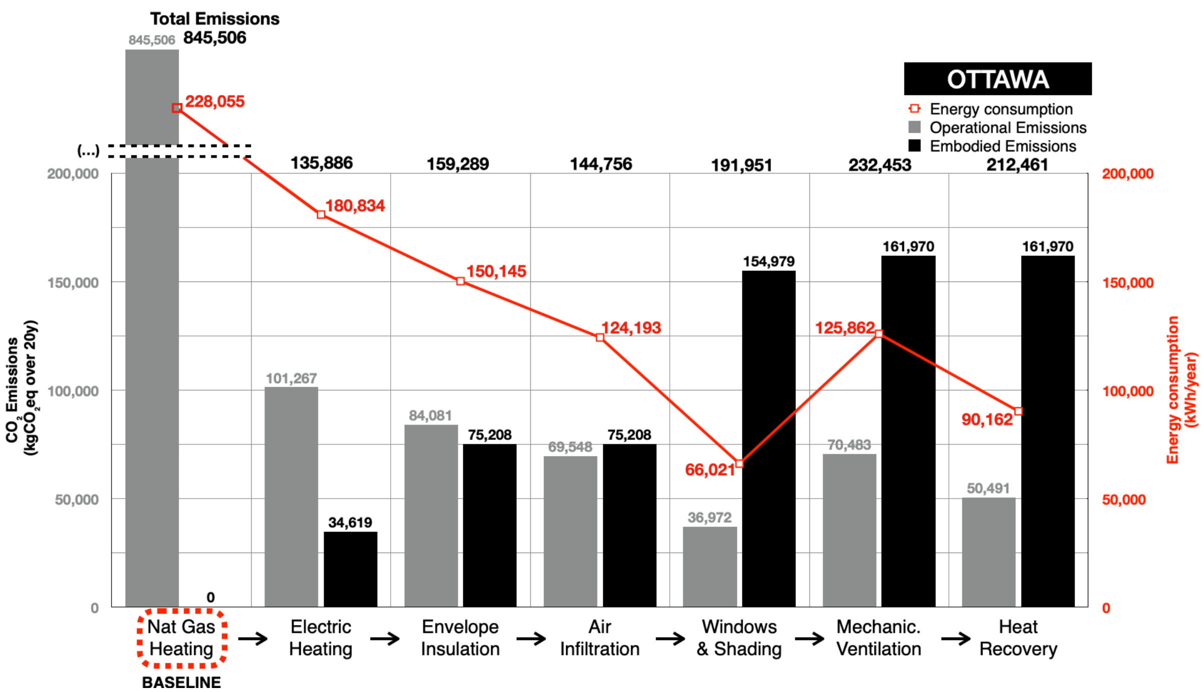


Figure 27. Energy use and carbon emissions (embodied and operational) calculated at each retrofit step, considering Ottawa location.

4.3.2.1 Outcomes (Ottawa)

Table 26. Comparison of results for Ottawa, baseline versus full retrofit.

	Baseline (a) (NAT GAS HEATING)	Baseline (b) (ELECTR. HEATING)	Full Retrofit (c) (ELECTR. HEATING)	VARIATION	
				(a) to (c)	(b) to (c)
Total Annual Energy Use (kWh/year)	**228,055**	**180,834**	**90,162**	**-137,893**	**-90,672**
Space Heating	188,884	141,663	45,282	(-60%)	(-50%)
Interior Lighting	27,248	27,248	9,033		
Computers/Plugs	11,923	11,923	11,706		
Mech. Ventilation w/ heat recovery	0	0	24,141		
Total Emissions (kgCO_2eq over 20y)	**845,506**	**135,886**	**212,461**	**-633,045**	**+76,575**
Operational Emissions	845,506	101,267	50,491	(-75%)	(+56%)
Embodied Emissions	0	34,619	161,970		

According to the CER (2020) reports, Electricity generation in the province of Ontario is mainly sourced from nuclear (59%), hydro (24%), wind (8%), and natural gas (7%) power. In contrast to Quebec, that exclusively relies on renewables, these differences result in Ontario having a grid electricity GHG intensity of 0.028 kgCO_2eq/kWh, which is 2.7 times more intense than that of Quebec (0.01023 kgCO_2eq/kWh), as outlined in section 4.2.3.

From the baseline (a) to the full retrofit (c), there is a reduction of 137,893 kWh/year in total energy use, primarily in the energy demand for space heating, attributed to the enhancements made to the building envelope and improved COP from the electric heating system. Meanwhile, total emissions decrease 633,045 kgCO_2eq, notably due to the savings in operational energy use emissions, which are attributed to the replacement of natural gas with electric heating. As a result, the transition from (a) to (c) yields significant reductions, outweighing any potential increases in embodied emissions associated with the production of materials and equipment.

However, when examining the transition from (b) to (c), where we assumed that the baseline already includes electric heating in the pre-retrofit situation, the conclusions are similar to the ones discussed for Montreal. While there is a reduction of 90,672 kWh/year in total energy use (provided by the envelope improvements), there is an increase of 76,575 kgCO_2eq in total life cycle emissions. Again, in this current situation of energy profile, the decision to undertake a retrofit may not appear justified solely from a carbon emissions perspective if the existent building already makes use of electric heating. Nevertheless, we must turn to point out the importance of enhancing the energy efficiency of buildings, given the expected increase of electricity demand in the coming decades, and the potential reintroduction of non-renewable sources to meet this increased demand.

4.3.3 Results for Halifax (Nova Scotia)

In the context of Halifax, located in the province of Nova Scotia, the results yielded contrasting conclusions compared to those reached for Montreal and Ottawa.

According to the CER (2020) reports, the primary sources of electricity generation in Nova Scotia are fossil fuels, specifically coal (52%), natural gas (22%), and petroleum (2%). Renewables constitute a smaller portion, accounting for 24% of the electricity mix. Considering this background, Nova Scotia presents an intriguing setting where the deployment of natural gas as a substitute for coal could potentially mitigate part of the grid's carbon footprint. This transitional/temporary approach could contribute to a reduction in emissions as the province expands its access to renewable sources.

The analyses conducted for Montreal and Ottawa involved the use of electric heating on the full retrofit scenario. For the case of Halifax, besides the electric heating retrofit approach, we explore an additional full retrofit configuration that does not entail the replacement of the natural gas heating. It's also important to highlight the distinct order of magnitude of carbon emissions for the Nova Scotia scenario, which required adjusting a new scale for the bar charts presented in this section.

4.3.3.1 Outcomes (Halifax, electric heating scenario)

Initially, we followed the same procedure as in the previous analyses, replacing the natural gas heating with an electric system. In this first step, labeled as 'Natural Gas Heating → Electric Heating' in Table 27 and Figure 28, it's possible to see that total energy use reduces from 185,704 to 149,121 kWh/year. This is solely due to the decrease in space heating demand, which drops from 146,334 to 109,751 kWh/year, as we assumed a thermal efficiency of 0.75 for natural gas heating and a coefficient of performance (COP) of 1 for electric heating.

However, the total life cycle emissions increase from 1,173,477 to 2,062,665 kgCO2eq over 20 years. This represents a rise of 889,188 kgCO2eq, with 96% of the increase due to operational emissions and the remaining 4% attributed to embodied emissions. As Nova Scotia primarily relies on fossil fuels for generating electricity, when we switch from the natural gas heating , it's expected that this increase would occur. This is because the electricity grid in Nova Scotia produces more

GHG emissions itself (i.e., 0.680 kgCO2eq/kWh, see section 4.2.3.3) than burning natural gas for space heating (i.e., 0.218 kgCO2eq/kWh (equivalent with 2.30 $kgCO_2eq/m^3$), see section 4.2.3.4).

Although the total emissions in the final stage of the retrofit (identified as "Heat Recovery" in Table 27 and Figure 28) are slightly lower than those for the baseline that utilizes natural gas heating (specifically, 1,173,477 kgCO2eq versus 1,127,387 kgCO2eq), it would still be more favorable in terms of carbon emissions to retain the use of natural gas heating in Nova Scotia, as elaborated in the subsequent section.

Table 27. Total energy use and total emissions calculated at each retrofit stage, considering Halifax location, electric heating approach.

	Natural Gas Heating →	Electric Heating →	Envelope Insulation→	Air Infiltration →	Windows & Shading →	Mech. Vent. →	Heat Recovery
Total Annual Energy Use [kWh/year]	**185,704**	**149,121** (-36,583)	**123,260** (-25,861)	**101,640** (-21,620)	**50,112** (-51,528)	**98,799** (+48,687)	**70,987** (-27,812)
Space Heating	146,334	109,751	84,592	62,972	29,833	29,833	29,833
Interior Lighting	27,447	27,447	26,962	26,962	8,573	8,573	8,573
Computers/Plugs	11,923	11,923	11,706	11,706	11,706	11,706	11,706
Mech. Ventilation	0	0	0	0	0	48,687	20,874
Total Emissions [$kgCO_2e$ over 20y]	**1,173,477**	**2,062,665** (+889,188)	**1,751,539** (-311,126)	**1,457,509** (-300,030)	**836,504** (-601,005)	**1,505,643** (+669,139)	**1,127,387** (-378,256)
Operational Emissions	1,173,477	2,028,046	1,676,331	1,382,301	681,525	1,343,673	965,417
Embodied Emissions	0	34,619	75,208	75,208	154,979	161,970	161,970

Obs.: The values displayed between parenthesis, for instance (–36,583), represent the relative variation of results at each calculation step.

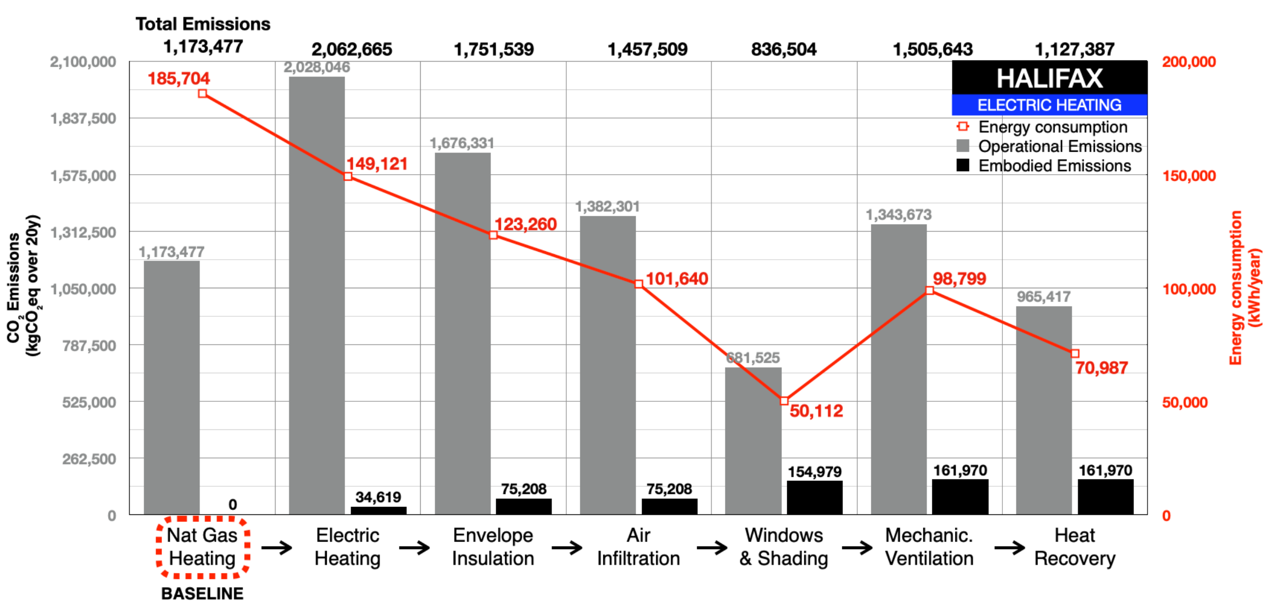


Figure 28. Energy use and carbon emissions (embodied and operational) calculated at each retrofit step, considering Halifax location, electric heating approach.

4.3.3.2 Outcomes (Halifax, keeping natural gas heating)

As shown in Table 28 and Figure 29, in the scenario where the natural gas heating system remains unchanged throughout the retrofit process both operational emissions and embodied emissions present significant reductions at each step of the retrofit. In contrast to the earlier scenario where the electric heating was implemented (see Figure 28), we can see in Figure 29 an overall reduction in operational emissions, associated with the reliance on natural gas system and improvements made to the building envelope. Meanwhile, the slightly lower levels of embodied emissions result from the non-inclusion of electric heating equipment, which would incur a manufacturing impact of 34,619 kgCO_2eq, as described in section 4.2.4.4.

Table 28. Total energy use and total emissions calculated at each retrofit stage, considering Halifax location, natural gas heating approach.

	Natural Gas Heating →	Electric Heating →	Envelope Insulation →	Air Infiltration →	Windows & Shading →	Mech. Vent. →	Heat Recovery
Total Annual Energy Use [kWh/year]	**185,704**		**151,456** (-34,248)	**122,630** (-28,826)	**60,057** (-62,573)	**98,799** (+38,742)	**80,931** (-17,868)
Space Heating (gas)	146,334		112,789	83,963	39,778	39,778	39,778
Interior Lighting	27,447		26,962	26,962	8,573	8,573	8,573
Computers/Plugs	11,923		11,706	11,706	11,706	11,706	11,706
Mech. Ventilation	0		0	0	0	38,742	20,874
Total Emissions [kgCO_2e over 20y]	**1,173,477**		**1,058,247** (-115,230)	**932,560** (-125,687)	**569,595** (-362,965)	**1,103,486** (+533,891)	**860,473** (-243,013)
Operational Emissions	1,173,477		1,017,658	891,971	449,235	976,132	733,122
Embodied Emissions	0		40,589	40,589	120,360	127,351	127,351

Obs.: The values displayed between parenthesis, for instance (–34,248), represent the relative variation of results at each calculation step.

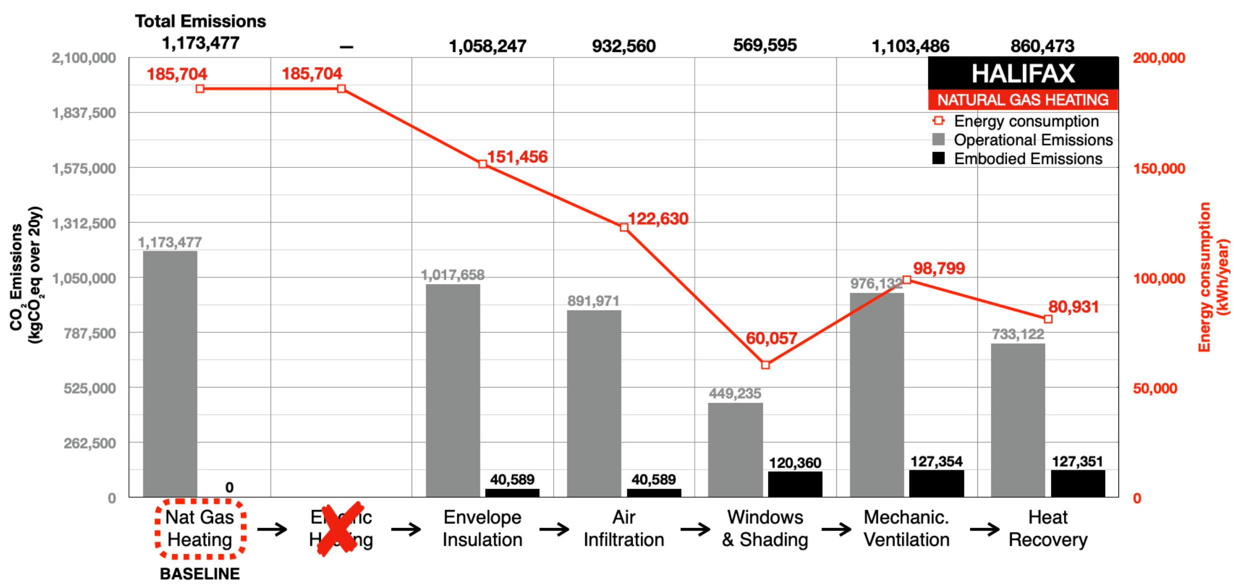


Figure 29. Energy use and carbon emissions (embodied and operational) calculated at each retrofit step, considering Halifax location, natural gas heating approach.

4.3.3.3 Comparison of Outcomes for both Halifax scenarios

As shown in Table 29, for the case of Halifax, instead of comparing two baseline designs with one full retrofit as we did for Montreal and Ottawa, we compared the existent design (baseline (a), reliant on natural gas heating) with two retrofit solutions (full retrofit (b), adding the electric heating, and full retrofit (c) keeping the natural gas heating).

Table 29. Comparison of results for both Halifax scenarios, baseline versus full retrofit approaches.

	Baseline (a) (NAT GAS HEATING)	Full Retrofit (b) (ELECTR. HEATING)	Full Retrofit (c) (NAT GAS HEATING)	VARIATION (a) to (b)	VARIATION (a) to (c)
Total Annual Energy Use (kWh/year)	**185,704**	**70,987**	**80,931**	**-114,717**	**-104,773**
Space Heating	146,334	29,833	39,778	**(-62%)**	**(-56%)**
Interior Lighting	27,447	8,573	8,573		
Computers/Plugs	11,923	11,706	11,706		
Mech. Ventilation w/ heat recovery	0	20,874	20,874		
Total Emissions (kgCO$_2$eq over 20y)	**1,173,477**	**1,127,387**	**860,473**	**-46,090**	**-313,004**
Operational Emissions	1,173,477	965,417	733,122	**(-4%)**	**(-27%)**
Embodied Emissions	0	161,970	127,351		

From (a) to (b), where the full retrofit included the replacement of natural gas heating with an electric system, the total annual energy use reduces in 114,717 kWh/year, while the total life cycle carbon emissions reduced 46,090 kgCO2eq over 20 years.

However, the transition from (a) to (c) yielded even more favorable outcomes. While the reduction in total annual energy consumption was slightly lower (i.e., 104,773 kWh/year) than in the previous scenario (i.e., 114,717 kWh/year), this difference is only attributed to the thermal efficiency of 0.75 considered for natural gas heating versus the COP=1 considered for electric heating. In terms of total emissions, the carbon reduction achieved from (a) to (c) (i.e., 313,004 kgCO$_2$eq) are approximately 7 times greater than those from (a) to (b) (i.e., 46,090 kgCO$_2$eq). The primary driver behind this improvement was the savings in operational emissions, as the use of natural gas for space heating carries a lower carbon footprint than relying on grid-purchased electricity in Nova Scotia. Furthermore, the shift from (a) to (c) also resulted in reduced embodied emissions, as the electric heating equipment was not added to the design.

In summary, the results show that all retrofit scenarios evaluated from the perspective of Halifax (Nova Scotia), offered advantages in both total annual energy consumption and overall life cycle emissions, but the natural gas heating scenario yielded lower environmental impacts.

These findings indicate that the decision to undertake this retrofit in Nova Scotia may be justified from both energy and carbon emissions perspectives.

4.3.4 Summary of Results (all cities)

The final outcomes for all locations and retrofit scenarios discussed in Chapter 4 are presented on the Table 27 and Figures Figure 30 and Figure 31. All bar charts in Figure 30 have been standardized to a common scale, facilitating a clear comparison between the contrasting order of magnitude Halifax' operational emissions.

Table 30. Summary of final outcomes for all cities, baseline versus full retrofit approaches.

	BASELINE (GAS HEATING)			**BASELINE [1]** (ELECTR. HEATING)			**FULL RETROFIT [2]**			
	Montreal	**Ottawa**	**Halifax**	**Montreal**	**Ottawa**	**Halifax**	**Montreal** (ELEC HEAT	**Ottawa** (ELECT HEAT)	**Halifax** (ELECT HEAT)	**Halifax [3]** (GAS HEATING)
Total Energy Use (kWh/year)	**188,555**	**228,055**	**185,704**	**151,201**	**180,834**	**149,121**	**75,351**	**90,162**	**70,987**	**80,931**
Space Heating	149,416	188,884	146,334	112,062	141,663	109,751	33,807	45,282	29,833	39,778
Interior Lighting	27,216	27,248	27,447	27,216	27,248	27,447	10,362	9,033	8,573	8,573
Computers/Plugs	11,923	11,923	11,923	11,923	11,923	11,923	11,706	11,706	11,706	11,706
Mech. Ventilation	0.0	0.0	0.0	0.0	0.0	0.0	19,476	24,141	20,874	20,874
Total Emissions (kgCO2e over 20y)	**659,493**	**845,506**	**1,173,477**	**65,567**	**135,886**	**2,062,665**	**177,393**	**212,461**	**1,127,387**	**860,473**
Operational Emissions	659,493	845,506	1,173,477	30,948	101,267	2,028,046	15,423	50,491	965,417	733,122
Embodied Emissions	0.0	0.0	0.0	34,619	34,619	34,619	161,970	161,970	161,970	127,351

[1] Same design as the original baseline, only switching to electric heating system. Also, the energy consumption is the same as the gas scenario, since the simulation is working on heat demand.
[2] Full retrofit design including improved envelope and windows, overhangs, mechanical ventilation, and heat recovery.
[3] Full retrofit design including all the improvements aforementioned but keeping the natural gas heating system instead of switching to electric heating.

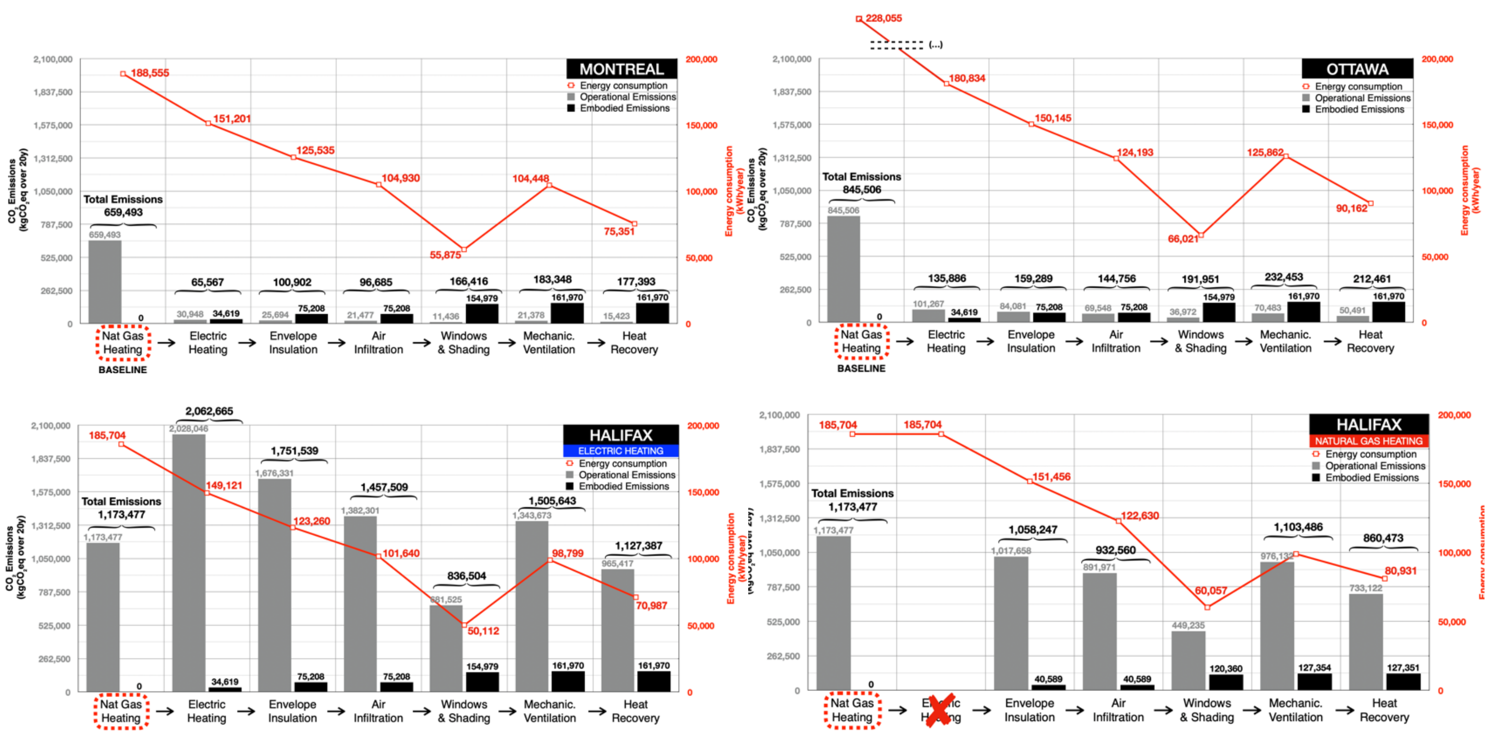


Figure 30. Comparison of the three cities showing the results for each retrofit improvement.

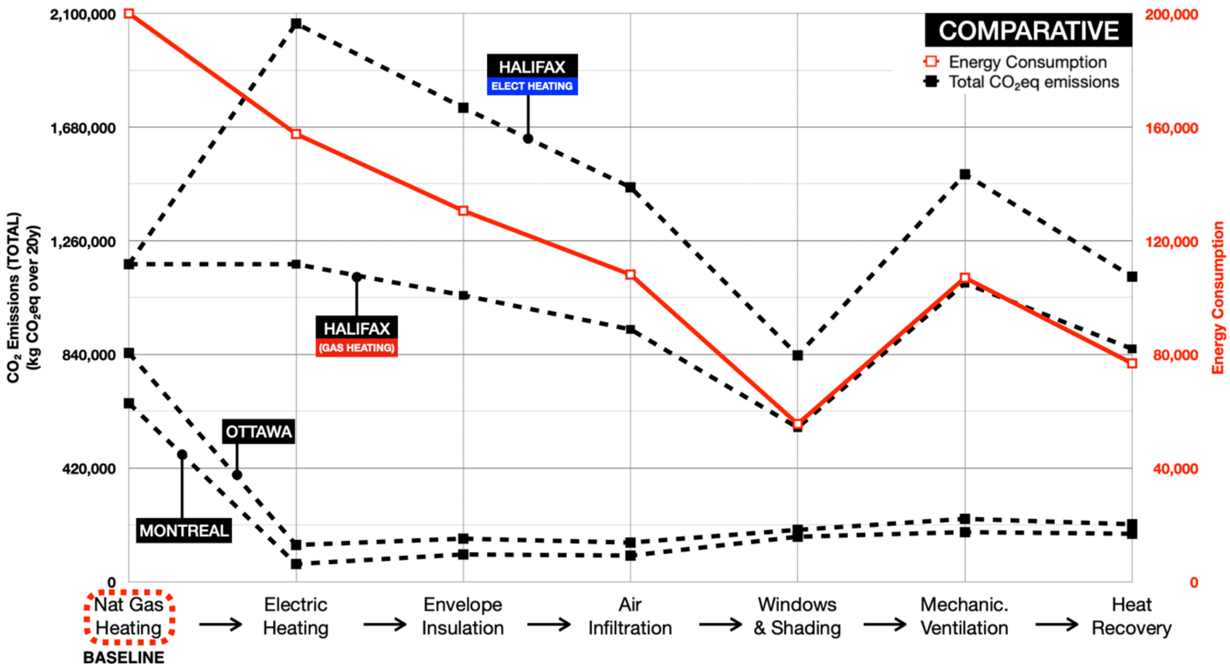


Figure 31. Comparison of results for all cities, total emissions and annual energy use.

4.3.5 Additional Scenarios with Heat Pumps (COP=2)

To verify the potentially different outcomes, we evaluated an additional scenario involving the use of heat pumps (COP=2) instead of electric heating (COP=1). The only region where this scenario could potentially change our conclusions is Nova Scotia, due to its high GHG intensity in electricity generation. Enhancing the COP in regions with a low-carbon grid such as Quebec and Ontario would only emphasize the significance of embodied emissions contributions.

As demonstrated in the tables presented in the Appendix, our conclusions remain the same. In Nova Scotia, adopting the heat pump approach leads to a slight reduction in operational emissions. However, as previously discussed in this thesis, it is still more advantageous to maintain natural gas heating for this location. The results for other scenarios adopting a longer calculation period (60 years), as well as the results for heat pumps for the other locations can be found in the Appendix.

4.4 Conclusion

This chapter presented the case study of a school building retrofit, and used energy simulations and life cycle assessment to evaluate whether the savings in operational energy use emissions resulting from the retrofit solution can outweigh the embodied emissions tied to the manufacturing of new materials incorporated into the enhanced design. The analysis was conducted under three location scenarios (i.e., Montreal, Ottawa, and Halifax). The findings underscore the significance of building/energy retrofit in places where the grid-electricity relies on fossil fuel, such as Nova Scotia. However, this also prompts a discussion about the extent of the benefits in locations where electricity is currently sourced from renewables. In places like Quebec and Ontario, if the existent case study building already relied on electricity for space heating, the embodied emissions associated with new materials and equipment might outweigh the operational emissions savings resulting from the retrofit.

In the cases of Montreal and Ottawa, the incorporation of electric heating and envelope improvements could potentially reduce the total life cycle emissions by 73% in the Montreal scenario (from 659,493 to 177,393 kgCO_2eq) and by 75% in the Ottawa scenario (from 845,506 to 212,461 kgCO_2eq). The shift from natural gas heating was the primary driver for emissions reduction, as the grid-electricity in these locations is generated from renewable sources.

However, when we assume that the baseline design (prior to retrofit) already relies on electric heating, the conclusions were significantly different. Since the current electricity generation in Quebec and Ontario is based on renewable sources, the carbon offset that can be potentially achieved with energy savings is limited in these locations. As a result, the reduction in operational emissions is unable to outweigh the embodied emissions associated with producing new materials and HVAC components incorporated to the design. For the Montreal scenario, the total life cycle emissions increased from 65,567 to 177,393 kgCO_2eq, while for the Ottawa scenario, increased from 135,886 to 212,461 kgCO_2eq.

But more important than the numeric results, is the general idea discussed in this chapter about the relative influence of embodied emissions and the relation between the local energy profiles of different provinces and the carbon offset potentially achieved with building/energy retrofit. The development of energy efficient buildings is valid in any context. But in this specific scenario of Quebec and Ontario, the decision to undertake a retrofit may not appear justified solely from a carbon perspective. Yet, these conclusions might change in the coming decades with the increase of electric vehicles and global population pressuring the reintroduction of non-renewable sources to meet the increased demand for electricity.

In contrast with the Montreal and Ottawa scenarios, the results for the Halifax (Nova Scotia) yielded distinct conclusions. Since the grid-purchased electricity in Nova Scotia is generated from fossil fuels (primarily coal), the carbon offset that can be achieved with energy savings is notably more substantial than that in Quebec and Ontario. From the baseline scenario (gas heating) to the full retrofit scenario (electric heating), the total emissions reduced by 4% (from 1,173,477 to 1,127,387 kgCO_2eq). However, Nova Scotia presents an intriguing situation where the use of natural gas heating results in a lower carbon footprint than the use of electric heating. Hence, an additional analysis was provided incorporating all the retrofit enhancements, but retaining the natural gas system for space heating. In this scenario, the total life cycle emissions reduced by 27% (from 1,173,477 to 860,474 kgCO_2eq). Therefore, the results show that all retrofit scenarios evaluated from the perspective of Halifax offered advantages in terms of carbon emissions reduction, but the scenario using natural gas yielded lower environmental impacts than switching to electric heating.

5 Thesis Findings and Conclusions

Manuscript #1 presented a Life Cycle Assessment (LCA) framework and general approach, applied to real case studies, to address the feasibility of planting trees around buildings as a nature-based solution of carbon sequestration. The study first outlines the potential of trees to absorb CO_2 emissions through photosynthesis, and the methods used for the estimation of annual carbon sequestration rates. Then, the carbon life cycle assessment of an all-electric laboratory at Concordia University and of a single-detached house (both located in Montreal) were presented. The LCA calculation was performed using two software tools, One Click LCA and Athena Impact Estimator for Buildings. The results in terms of Global Warming Potential (GWP) over 60 years for the laboratory were found to be 83,521 $kgCO_2eq$ using One Click LCA, and 82,666 $kgCO_2eq$ using Athena. For the single-detached house that uses natural gas for space heating and domestic hot water, the GWP was found to be 544,907 $kgCO_2eq$ using One Click LCA, and 566,856 $kgCO_2eq$ using Athena. For the all-electric laboratory, a garden fully covered with representative urban trees could offset around 17% of the total life cycle carbon emissions. For the natural gas-powered single-detached house, the sequestration by trees is around 3% of the total life cycle carbon emission. Therefore, based on the outcomes presented in this study, it seems to be possible to achieve a carbon balance closer to net-zero when expanding the strategies with approaches including other types of greeneries and on-site electricity generation. Coupling those strategies with the indirect benefits of vegetation (i.e., energy savings), the use of bio-based materials, and the use of recyclable/reusable materials may be a consistent pathway towards the design and operation of carbon neutral buildings.

Manuscript #2 expands the results from Manuscript #1, showing a different perspective of the practical significance and potential benefits of nature-based design solutions. Using the case of the Future Buildings Laboratory, this study focused on demonstrating how to quantify and report the benefits associated with biogenic carbon content in wood products and end-of-life treatment of materials. The analysis was provided under three end-of-life scenarios for wood products: wood incineration with energy recovery, wood landfilling, and wood recycling/repurposing. The results indicated that the set of strategies adopted in this building, i.e., the use of wood products, benefits from end-of-life treatment of materials, and carbon sequestration from trees can potentially offset building's carbon emission by 37.2% up to 83.9% when included in the LCA, depending on the scenario considered.

Finally, an additional approach was presented after the two manuscripts. This approach focused on the application of LCA in the context of building/energy retrofit design. The case study of a 2-storey natural gas-heated school building was used to assess whether the savings in operational energy resulting from the retrofit could outweigh the impacts of embodied emissions tied to the manufacturing of new envelope and HVAC components. Given the relevance of local electricity-grid profile on the environmental performance outcomes, the simulations in this part have been conducted for three different locations across Canada (Montreal, Ottawa, and Halifax). The findings underscore the significance of building/energy retrofit in places where the grid-electricity relies on fossil fuel, such as Nova Scotia. However, it also prompts a discussion about the extent of the benefits in locations where electricity is currently sourced from renewables. The conclusion was that in places like Quebec and Ontario, where the grid-electricity is generated from renewable sources, the decision to undertake a retrofit in buildings that already rely on electric heating may not appear justified solely from a carbon emissions perspective. But this doesn't mean that energy retrofit shouldn't be supported and promoted. The electrification of transportation sector and the populational growth is likely to cause an increase on the demand for electricity, which can result on the reintroduction of non-renewable sources in order to meet this demand.

On the other hand, for buildings relying on natural gas heating, or located in places like Nova Scotia, where the grid-electricity is sourced from fossil fuels, the carbon offset provided by energy savings may outweigh any impacts of embodied emissions from the new components incorporated to the retrofit design.

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Appendix

Montreal, Quebec
20 years
Thermal efficiency=0.75 (gas heating)
COP=2 (heat pump)

	Baseline (a) (NAT GAS HEATING)	Baseline (b) (HEAT PUMP)	Full Retrofit (c) (HEAT PUMP)	VARIATION (a) to (c)	VARIATION (b) to (c)
Total Annual Energy Use (kWh/year)	188,555	**95,170**	**58,447**	**-130,108** (-69%)	**-36,723** (-38%)
Space Heating	149,416	56,031	16,903		
Interior Lighting	27,216	27,216	10,362		
Computers/Plugs	11,923	11,923	11,706		
Mech. Ventilation w/ heat recovery	0	0	19,476		
Total Emissions (kgCO_2eq over 20y)	**659,493**	**54,098**	**173,933**	**-485,560** (-74%)	**+119,835** (+221%)
Operational Emissions	659,493	19,479	11,963		
Embodied Emissions	0	34,619	161,970		

Montreal, Quebec
60 years
Thermal efficiency=0.75 (gas heating)
COP=2 (heat pump)

	Baseline (a) (NAT GAS HEATING)	Baseline (b) (HEAT PUMP)	Full Retrofit (c) (HEAT PUMP)	VARIATION (a) to (c)	VARIATION (b) to (c)
Total Annual Energy Use (kWh/year)	188,555	**95,170**	**58,447**	**-130,108** (-69%)	**-36,723** (-38%)
Space Heating	149,416	56,031	16,903		
Interior Lighting	27,216	27,216	10,362		
Computers/Plugs	11,923	11,923	11,706		
Mech. Ventilation w/ heat recovery	0	0	19,476		
Total Emissions (kgCO_2eq over 60y)	**1,978,479**	**162,787**	**357,679**	**-1,620,800** (-82%)	**+194,892** (+119%)
Operational Emissions	1,978,479	58,438	35,889		
Embodied Emissions	0	104,349	321,790		

Montreal, Quebec
60 years
Thermal efficiency=0.75 (gas heating)
COP=1 (electric heating)

	Baseline (a) (NAT GAS HEATING)	Baseline (b) (ELECTR. HEATING)	Full Retrofit (c) (ELECTR. HEATING)	VARIATION (a) to (c)	VARIATION (b) to (c)
Total Annual Energy Use (kWh/year)	188,555	151,201	75,351	-113,204 (-60%)	-75,850 (-50%)
Space Heating	149,416	112,062	33,807		
Interior Lighting	27,216	27,216	10,362		
Computers/Plugs	11,923	11,923	11,706		
Mech. Ventilation w/ heat recovery	0.0	0.0	19,476		
Total Emissions (kgCO_2eq over 60y)	**1,978,479**	**197,193**	**368,059**	**-1,610,420** (-81%)	**+170,866** (+86%)
Operational Emissions	1,978,479	92,844	46,269		
Embodied Emissions	0	104,349	321,790		

Ottawa, Ontario
20 years
Thermal efficiency=0.75 (gas heating)
COP=2 (heat pump)

	Baseline (a) (NAT GAS HEATING)	Baseline (b) (HEAT PUMP)	Full Retrofit (c) (HEAT PUMP)	VARIATION (a) to (c)	(b) to (c)
Total Annual Energy Use (kWh/year)	**228,055**	**110,002**	**67,521**	**-160,534** (-70%)	**-42,482** (-39%)
Space Heating	188,884	70,832	22,641		
Interior Lighting	27,248	27,248	9,033		
Computers/Plugs	11,923	11,923	11,706		
Mech. Ventilation w/ heat recovery	0	0	24,141		
Total Emissions (kgCO_2eq over 20y)	**845,506**	**96,220**	**199,781**	**-654,724** (-76%)	**+103,561** (+107%)
Operational Emissions	845,506	61,601	37,812		
Embodied Emissions	0	34,619	161,970		

Ottawa, Ontario
60 years
Thermal efficiency=0.75 (gas heating)
COP=2 (heat pump)

	Baseline (a) (NAT GAS HEATING)	Baseline (b) (HEAT PUMP)	Full Retrofit (c) (HEAT PUMP)	VARIATION (a) to (c)	(b) to (c)
Total Annual Energy Use (kWh/year)	**228,055**	**110,002**	**67,521**	**-160,534** (-70%)	**-42,482** (-39%)
Space Heating	188,884	70,832	22,641		
Interior Lighting	27,248	27,248	9,033		
Computers/Plugs	11,923	11,923	11,706		
Mech. Ventilation w/ heat recovery	0	0	24,141		
Total Emissions (kgCO_2eq over 60y)	**2,536,517**	**289,153**	**435,225**	**-2,101,292** (-83%)	**+146,072** (+50%)
Operational Emissions	2,536,517	184,804	113,435		
Embodied Emissions	0	104,349	321,790		

Ottawa, Ontario
60 years
Thermal efficiency=0.75 (gas heating)
COP=1 (electric heating)

	Baseline (a) (NAT GAS HEATING)	Baseline (b) (ELECTR HEATING)	Full Retrofit (c) (ELECTR. HEATING)	VARIATION (a) to (c)	(b) to (c)
Total Annual Energy Use (kWh/year)	**228,055**	**180,834**	**90,162**	**-137,892** (-60%)	**-90,672** (-50%)
Space Heating	188,884	141,663	45,282		
Interior Lighting	27,248	27,248	9,033		
Computers/Plugs	11,923	11,923	11,706		
Mech. Ventilation w/ heat recovery	0	0	24,141		
Total Emissions (kgCO_2eq over 60y)	**2,536,517**	**408,149**	**473,262**	**-2,063,225** (-81%)	**+65,112** (+16%)
Operational Emissions	2,536,517	303,800	151,472		
Embodied Emissions	0	104,349	321,790		

Halifax, Nova Scotia
20 years
Thermal efficiency=0.75 (gas heating)
COP=2 (heat pump)

	Baseline (a) (NAT GAS HEATING)	Baseline (b) (HEAT PUMP)	Full Retrofit (c) (HEAT PUMP)	VARIATION (a) to (c)	VARIATION (b) to (c)
Total Annual Energy Use (kWh/year)	185,704	**94,246**	**70,987**	**-114,717** (-62%)	**-23,259** (-24%)
Space Heating	146,334	54,876	14,917		
Interior Lighting	27,447	27,447	8,573		
Computers/Plugs	11,923	11,923	11,706		
Mech. Ventilation w/ heat recovery	0	0	35,791		
Total Emissions (kgCO₂eq over 20y)	**1,173,477**	**1,316,359**	**1,127,387**	**-46,090** (-4%)	**-188,972** (-14%)
Operational Emissions	1,173,477	1,281,740	965,417		
Embodied Emissions	0	34,619	161,970		

Halifax, Nova Scotia
60 years
Thermal efficiency=0.75 (gas heating)
COP=2 (heat pump)

	Baseline (a) (NAT GAS HEATING)	Baseline (b) (HEAT PUMP)	Full Retrofit (c) (HEAT PUMP)	VARIATION (a) to (c)	VARIATION (b) to (c)
Total Annual Energy Use (kWh/year)	185,704	**94,246**	**70,987**	**-114,717** (-62%)	**-23,259** (-24%)
Space Heating	146,334	54,876	14,917		
Interior Lighting	27,447	27,447	8,573		
Computers/Plugs	11,923	11,923	11,706		
Mech. Ventilation w/ heat recovery	0	0	35,791		
Total Emissions (kgCO₂eq over 60y)	**3,520,432**	**3,949,570**	**3,218,042**	**-302,390** (-9%)	**-731,528** (-18%)
Operational Emissions	3,520,432	3,845,221	2,896,252		
Embodied Emissions	0	104,349	321,790		

Halifax, Nova Scotia
60 years
Thermal efficiency=0.75 (gas heating)
COP=1 (electric heating)

	Baseline (a) (NAT GAS HEATING)	Baseline (b) (ELECTR. HEATING)	Full Retrofit (c) (ELECTR. HEATING)	VARIATION (a) to (c)	VARIATION (b) to (c)
Total Annual Energy Use (kWh/year)	185,704	149,121	70,987	-114,717 (-62%)	-78,134 (-52%)
Space Heating	146,334	109,751	29,833		
Interior Lighting	27,447	27,447	8,573		
Computers/Plugs	11,923	11,923	11,706		
Mech. Ventilation w/ heat recovery	0	0	20,874		
Total Emissions (kgCO₂eq over 60y)	**3,520,432**	**6,188,486**	**3,218,042**	**-302,390** (-9%)	**-2,970,444** (-48%)
Operational Emissions	3,520,432	6,084,137	2,896,252		
Embodied Emissions	0	104,349	321,790		

Halifax, Nova Scotia

60 years

Thermal efficiency=0.75 (GAS HEATING ONLY)

	Baseline (a) (NAT GAS HEATING)	Baseline (b) (ELECTRIC HEATING)	Full Retrofit (c) (GAS HEATING)	VARIATION (a) to (c)	VARIATION (b) to (c)
Total Annual Energy Use (kWh/year)	**185,704**		**80,931**		**-107,773** (-56%)
Space Heating	146,334		39,778		
Interior Lighting	27,447		8,573		
Computers/Plugs	11,923		11,706		
Mech. Ventilation w/ heat recovery	0		20,874		
Total Emissions (kgCO_2eq over 60y)	**3,520,432**		**2,416,806**		**-1,193,626** (-31%)
Operational Emissions	3,520,432		2,199,365		
Embodied Emissions	0		217,441		